The Environmental Protection Agency

Water Treatment Manual: Filtration

Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

ENVIRONMENTAL PROTECTION AGENCY

The EPA is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: *Implementing regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

Knowledge: *Providing high quality, targeted and timely environmental data, information and assessment to inform decision making.*

Advocacy: *Working with others to advocate for a clean, productive and well protected environment and for sustainable environmental practices.*

Our responsibilities include:

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- Large-scale industrial, waste and petrol storage activities;
- Urban waste water discharges;
- The contained use and controlled release of Genetically Modified Organisms;
- Sources of ionising radiation;
- Greenhouse gas emissions from industry and aviation through the EU Emissions Trading Scheme.

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- Audit and inspection of EPA licensed facilities;
- Drive the implementation of best practice in regulated activities and facilities;
- Oversee local authority responsibilities for environmental protection;
- Regulate the quality of public drinking water and enforce urban waste water discharge authorisations;
- Assess and report on public and private drinking water quality;
- Coordinate a network of public service organisations to support action against environmental crime;
- Prosecute those who flout environmental law and damage the environment.

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- Prepare and publish national waste statistics and the National Hazardous Waste Management Plan;
- Develop and implement the National Waste Prevention Programme;
- Implement and report on legislation on the control of chemicals in the environment.

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- Monitor, assess and report on the quality of rivers, lakes, transitional and coastal waters, bathing waters and groundwaters, and measurement of water levels and river flows.

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- Publish Ireland's greenhouse gas emission inventories and projections;
- Provide the Secretariat to the Climate Change Advisory Council and support to the National Dialogue on Climate Action;
- Support National, EU and UN Climate Science and Policy development activities.

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- Produce the State of Ireland's Environment and Indicator Reports;
- Monitor air quality and implement the EU Clean Air for Europe Directive, the Convention on Long Range Transboundary Air Pollution, and the National Emissions Ceiling Directive;
- Oversee the implementation of the Environmental Noise Directive;
- Assess the impact of proposed plans and programmes on the Irish environment.

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- Coordinate and fund national environmental research activity to identify pressures, inform policy and provide solutions;
- Collaborate with national and EU environmental research activity.

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- Monitor developments abroad relating to nuclear installations and radiological safety;
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- Provide independent evidence-based reporting, advice and guidance to Government, industry and the public on environmental and radiological protection topics;
- Promote the link between health and wellbeing, the economy and a clean environment;
- Promote environmental awareness including supporting behaviours for resource efficiency and climate transition;
- Promote radon testing in homes and workplaces and encourage remediation where necessary.

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- Work with international and national agencies, regional and local authorities, non-governmental organisations, representative bodies and government departments to deliver environmental and radiological protection, research coordination and science-based decision making.

Management and structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

Water Treatment Manual
Filtration

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Preface

The Environmental Protection Agency (EPA) was established in 1993 to license, regulate and control activities for the purposes of environmental protection. In the Environmental Protection Agency Act, 1992 (Section 60), it is stated that "the Agency may, and shall if so directed by the Minister, specify and publish criteria and procedures, which in the opinion of the Agency are reasonable and desirable for the purposes of environmental protection, in relation to the management, maintenance, supervision, operation or use of all or specified classes or plant, sewers or drainage pipes vested in or controlled or used by a sanitary authority for the treatment of drinking water . . . and a sanitary authority shall . . . have regard to such criteria and procedures".

The EPA first published its *Water Treatment Manual on Filtration* in 1995. Since the publication of this manual there have been developments in terms of the technologies available, best practice in filter operation and in the supervisory role of the EPA in the drinking water area. This manual has been prepared to reflect best practice in drinking water filtration.

The main changes to the manual include:

- integration of the drinking water safety plan approach throughout the manual;
- consideration of the "log credit approach";
- updating of all chapters to reflect current best practice;
- a new chapter on membrane filtration;
- a new chapter on pre-treatment filtration technologies;
- a new chapter on alternative and emerging filtration technologies.

CONTENTS

1. Introduction

One of the main objectives of drinking water treatment is the removal and/or inactivation of pathogenic microorganisms that could present a risk to human health. Filtration is a treatment process that is used to accomplish this goal, either by providing a mechanism to physically remove a pathogenic organism from the source water or by reducing suspended solids to protect downstream disinfection processes (e.g. ultraviolet disinfection, chlorine disinfection).

Filtration processes have been used in water treatment for several centuries. Early installations were what are now termed slow sand filtration plants and regarded as a means of simply straining out turbidity and suspended solids. Slow sand filtration was the main protection from waterborne diseases arising from contaminated sources until the early years of the 20th century, when chlorination started to be used as a disinfectant. The first rapid gravity sand filter was put into operation at Little Falls, New Jersey, in 1920. The driver for its development was to reduce the land take needed for the construction of slow sand filters, especially where upgrades of existing drinking water treatment plants (DWTPs) had to take place in confined sites.

Whilst original simple gravity and pressure filtration processes are still widely in use throughout the water industry and remain a primary tool in water treatment, the advent of new and higher regulatory standards for potable water supply has driven the development of new technologies designed to meet the challenges facing the industry, and this is particularly true of filtration.

1.1 Objective of this Manual

The objective of this filtration manual is to provide practical guidance and information on all current filtration technologies available to:

- water service authorities and private water suppliers, to allow them to design and operate water treatment systems with effective filtration processes;
- supervisory authorities for both public and private water supplies under the current drinking water regulations.

The Environmental Protection Agency's (EPA's) *Water Treatment Manual on Filtration* was published in 1995 as part of a series of water treatment manuals published between 1995 and 2002, covering both public and private water supplies. The manual presented comprehensive guidance on rapid gravity, slow sand and pressure filtration. This revised filtration manual details developments in filter technology and relevant regulations in the intervening period. Topics of particular focus include:

- The development of risk-based approaches to safeguarding drinking water quality using the drinking water safety planning approach.
- The recognition that many filtration processes also provide physical removal of potentially harmful organisms. Filtration contributes to the multi-barrier approach to drinking water treatment by providing a physical removal barrier upstream of a conventional disinfection process by chemical or ultraviolet inactivation. Filtration also reduces turbidity in the water treated by the filter to a level that allows effective disinfection of the final filtrate in downstream processes.
- Other filtration technologies not included in the original manual, such as membrane filtration and cartridge filtration.

1.2 Drinking Water Regulations

At the time of publication, the current drinking water regulations in Ireland are prescribed in the European Union (Drinking Water) Regulations 2014, SI No. 122/2014, as amended by SI No. 464/2017. The EPA has published handbooks on the implementation of the regulations to provide guidance to water suppliers for both public (EPA, 2010a) and private supplies (EPA, 2010b). The handbooks are available on the EPA website (www.epa.ie).

There are no regulations that apply directly and specifically to the operation of filtration processes. The one exception is the requirement to ensure that turbidity is reduced to below 1 nephelometric turbidity unit (NTU) before the application of chemical and/or ultraviolet disinfection processes.

Guidance issued in the *EPA Advice Note on Turbidity in Drinking Water* (EPA, 2009), advises that water treatment plants where filtration is implemented as a barrier for *Cryptosporidium* be optimised for turbidity of < 0.2 NTU.

Further information about the types of waterborne pathogens and the associated challenges to water treatment and disinfection approaches can be found in Chapter 2 of the *EPA Disinfection Manual* (EPA, 2011a).

1.3 Risk-based Approach to Management of Drinking Water Supplies

The integration of drinking water safety plans (DWSPs) into water treatment plant operations is recommended by the World Health Organization (WHO) (WHO, 2009a).

The key components of a drinking water safety plan are set out in the *EPA Advice Note on Developing Drinking Water Safety Plans* (EPA, 2011b).

The three key components are as follows:

- Source to tap risk assessment for a drinking water supply system, which includes the water treatment plant and distribution network. This involves identifying the potential **hazards** in each part of the system, the level of **risk** associated with each hazard and an appropriate **control measure**.
- Defining the required operational monitoring for each control measure to ensure that any deviation is rapidly detected. This can be any combination of operational tasks, online instrumentation and alarm set points.
- Documentation of the assessment, the required validation and operational monitoring and the required actions under normal and incident conditions.

Filtration processes are defined control measures at water treatment plants. For example:

- Coagulation, flocculation and clarification followed by rapid gravity filtration is an effective control measure against the hazard of *Cryptosporidium* in the source water.
- Visual inspection of a filter backwash is a control measure against an ineffective backwash.
- Air integrity testing is a control measure against the hazard of poor membrane asset condition in a membrane treatment plant, which could allow the breakthrough of *Cryptosporidium*.

1.4 Outline of Content and How to use this Manual

The structure of this water treatment manual is as follows:

- Introduction to filtration objectives and associated DWSP considerations.
- Detailed overview of identified core technologies used in Ireland including:
  - slow sand filtration;
  - rapid gravity filtration (RGF) and pressure filtration;
  - pre-filtration technologies;
  - granular activated carbon (GAC);
  - membrane filtration;
  - cartridge filtration;
  - combined clarification–filtration packaged systems.
- Outline overview of pre-treatment filtration technologies and basic considerations.
- Outline overview of alternative filtration technologies which include emerging technologies and existing technologies with limited current use in Ireland.

Each core technology is presented as a stand-alone chapter with the following structure:

- process overview;
- process equipment and layout;
- design considerations;
- guidance on operation;
- critical control parameters;
- upstream and downstream considerations;
- process start-up and shutdown;
- advantages and limitations.

It is recommended that water suppliers reference the relevant chapter for the technology of interest in conjunction with Chapters 1–3.

A glossary of terms and abbreviations is included before Appendix A.

2. FILTRATION APPLICATIONS AND OBJECTIVES

2.1 Overview of Filtration Mechanisms

There are two main types of mechanisms to consider in filtration processes:

- **Transport mechanisms:** how the particles come in contact with the filtration matrix (e.g. sand, membrane surface).
- **Removal mechanisms:** the mechanisms that physically remove a particle from the process water. This can include physical, chemical and biological mechanisms.

The dominant removal mechanisms that apply to drinking water media filtration are as follows:

- **Straining:** a size exclusion-based physical removal mechanism in which particles that are larger than the available pore space are physically removed from the filtered water.
- **Adsorption:** a physical or chemical mechanism in which a compound is removed when it attaches to a physical surface, either of the filter media or of previously deposited and/or adsorbed particles.
- **Biological removal:** a biological process in which a compound is removed through its conversion in a biological process.

The main transport mechanisms that allow the particle collision and/or capture to occur are as follows:

- **Interception:** a particle carried by a fluid comes in contact with the filter matrix.
- **Sedimentation:** a physical removal process in which particles settle in the available pore space in filtration media.
- **Diffusion:** a molecular process in which particles move randomly as a result of thermal gradients within the carrier fluid and come into contact with a media granule. This is typically effective only for small particles (< 1 µm).
- **Flocculation:** larger particles attach smaller particles, which will then become trapped within the filter matrix.

The exact mechanisms that contribute to the removal of a target compound or organism will vary depending on the selected filtration technology, the source water and operating conditions.

In membrane filtration technologies, the following two mechanisms are dominant:

- **Sieving:** the mechanism that applies to porous membranes. It occurs when suspended or colloidal particles are physically prevented from transport across a physical membrane as a result of size exclusion, i.e. the particle is larger than the pore(s) within the membrane material.
- **Reverse osmosis:** the mechanism that applies to semi-permeable membranes. Osmosis is the natural flow of a solvent across a membrane from a less concentrated solution to a more concentrated solution. The pressure that must be applied to the side of the membrane with the concentrated solution is called the osmotic pressure. Reverse osmosis is therefore the reverse of the natural osmotic pressure, and is achieved by applying pressure in excess of the osmotic pressure to the concentrated side. This forces the flow of solvent from the more concentrated (feed) to less concentrated (permeate or filtrate).

2.2 Conventional and Direct Filtration

The definitions are as follows:

- **Conventional filtration:** the term "conventional filtration" traditionally applies to water treatment plants in which coagulation, flocculation and clarification take place upstream of filtration. Briefly, these processes involve:
    - **Coagulation:** positively charged metal salts are added to the water and rapidly mixed to neutralise negatively charged particulates, colloidal and dissolved contaminants, resulting in the formation of floc particle agglomerations.
    - **Flocculation** (not always provided): a process of gentle water movement that promotes the collision and aggregation of small, destabilised particles (comprising metal hydroxide precipitates) into larger floc particles better suited for removal by clarification.
    - **Clarification:** separation of the formed precipitates using either settlement or flotation techniques.
    - **Filtration:** separation and removal of remaining suspended particulates within a filter media bed.
- **Direct filtration**: usually applied at DWTPs with good-quality source water, this involves the addition of a chemical coagulant with rapid mixing flocculation (not always provided), followed by media filtration.

The main difference between direct filtration and conventional filtration is the absence of a clarification process (i.e. settlement or flotation).

Figures 2.1 and 2.2 outline the typical process flow for conventional and direct filtration plants.

Figure 2.1: Conventional filtration

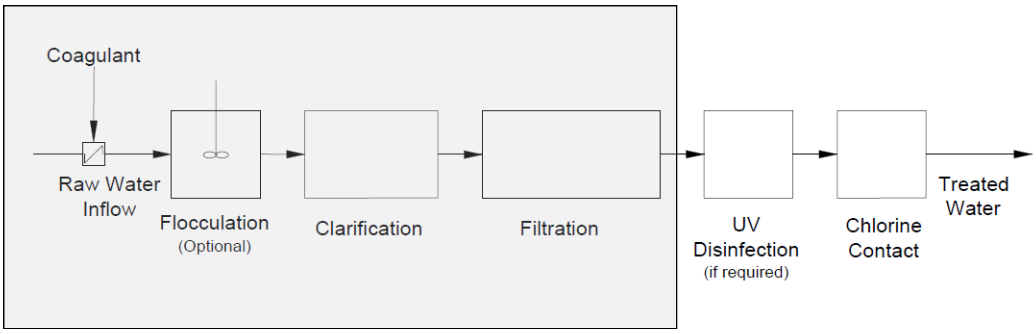
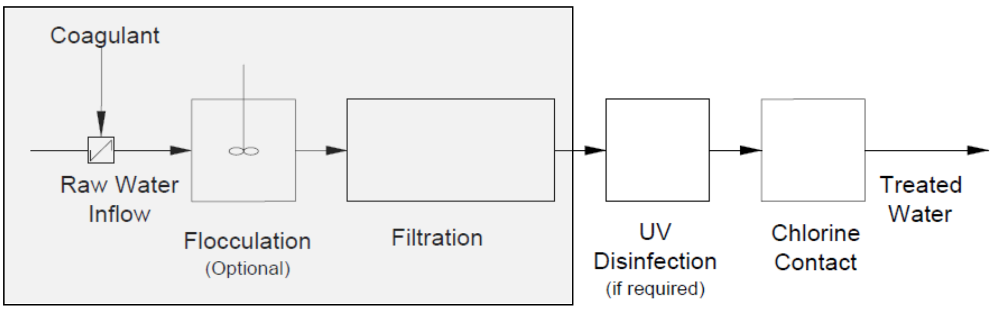


Figure 2.2: Direct filtration



The terms "direct filtration" and "conventional filtration" are used in both the United States Environmental Protection Agency (US EPA) and New Zealand regulations. When referring to these external documents it is important to recognise that the terms apply not to the specific filtration process, but to the whole end-to-end water treatment plant, as illustrated in Figures 2.1 and 2.2.

2.3 Filtration Objectives

Filtration objectives are defined as follows:

- **Pathogen removal**: the filtration process contributes to the overall disinfection strategy of a water treatment plant by removing potentially harmful organisms.
- **Turbidity reduction**: filtration reduces turbidity (general solids removal). This is often done to protect downstream processes and is applied at most water treatment plants to achieve a specific turbidity upstream of a chemical or ultraviolet disinfection process.
- **Organics reduction**: filtration contributes to organic reduction through physical removal of total organic carbon (TOC), adsorption of dissolved compounds or removal of floc particles and dissolved organic matter enmeshed within or adsorbed on the floc.
- **Metals removal**: filtration reduces target metals, typically through physical removal of particulates or adsorptions of soluble forms.
- **Pre-treatment filtration**: a filtration technology to protect a downstream treatment process.
- **Residuals treatment**: a filtration technology to treat process wastes to allow for recycling to the head of the DWTP or to achieve the quality required for discharge of water to sewer or the natural environment. Quality targets could include turbidity, metals residual and colour.

Many filters, especially filters at conventional water treatment plants, provide controls for multiple objectives. For example, a rapid gravity filter at a conventional water plant will provide physical removal of some pathogenic organisms, such as *Cryptosporidium*. The same filter will also remove any floc carryover from an upstream clarification stage. The concentration of fine particles will be reduced, which will reduce the TOC in the filtrate, which will have downstream benefits, reducing the potential for disinfection by-product (DBP) formation. Further details on disinfection by-products can be found in Chapter 3 of the *EPA Water Treatment Manual: Disinfection* (EPA, 2013).

Second-stage filters are often installed downstream of a primary filter to provide targeted reduction of specific compounds of concern (i.e. manganese, pesticides). Some examples of hazards and required controls are presented in Table 2.3.

2.4 Source Water Considerations

The selection of the most appropriate and cost-effective filtration technology for a given application requires an understanding of the quality and the variability of the source water. The source to tap approach of the drinking water safety planning process provides a framework for assessing the potential risks associated with source waters and catchments.

It is important that a source water risk assessment considers the following:

- **Source water variability**: some sources, such as lakes, are relatively stable but can experience significant changes in water quality during spring and autumn turnovers. Rivers are vulnerable to changing weather conditions and can bring substantial changes in water quality in a very short time. The alkalinity of the raw water can suddenly drop, leaving the raw water with insufficient alkalinity to facilitate proper coagulation and flocculation. This will cause water quality issues in treatment processes downstream of clarification and filtration.
- **Catchment risks**: catchment activities, such as manure spreading, land disturbance, pollution events, deforestation and pesticide use, can have a negative impact on source water quality and DWTP operations. In severe cases, such as pollution by silage effluent, milk or blood at close proximity to the raw water intake, the complete failure of the treatment plant can occur.
- **Operational controls**: appropriate operational controls (e.g. sampling, visual inspections, alarm triggers) need to be in place to respond to changes in water quality.

At some water treatment plants, the source water variability will require additional treatment steps to be put in place, including, for example:

- pH (acid or alkali) correction to counteract a rise in pH (e.g. due to algal blooms);
- addition of alkalinity and/or adjustment of pH to ensure sufficient alkalinity and optimal pH for coagulation;
- flocculation or additional upstream pre-treatment prior to the membrane stage to prevent higher turbidity loadings, which can reduce filter run times.

Plant operators should review the critical control parameters that could be affected by source water variability and ensure that sufficient operational controls are defined as required.

2.5 Drinking Water Safety Plans and Filtration Processes

Hazards to drinking water quality can be caused by a multitude of factors. These include insufficient treatment to mitigate a hazard that has arisen and/or increased as a result of poor operational practices or poor condition of existing assets. Some examples of hazards associated with filtration are outlined in Table 2.1. A comprehensive list of potential hazards associated with filtration is provided in Appendix A.

Table 2.1: Example DWSP hazards and controls for filtration

Hazard	Potential cause	Potential control measure
Inadequate treatment for *Cryptosporidium*	Absence of suitable filtration process with upstream coagulation to achieve required reduction	Installation of new treatment process
Inadequate treatment – inadequate disinfection	Filtration not reliably achieving turbidity target upstream of UV/chlorination disinfection	Improvement to filtration process operation, focusing on online monitoring of filtered turbidity and improvements to filter backwash. Review of adequacy of filter media to affect the filtered water quality required for the particular water

Hazard	Potential cause	Potential control measure
Inadequate process control (e.g. lack of turbidity monitors)	Continuous turbidity monitoring of individual filters not provided, with risk of breakthrough going undetected before combined filtered turbidity is affected	Install continuous turbidity monitoring
Backwash water recycled to head of DWTP, causing increased turbidity	Recycled water introduced before coagulant is added and can exceed 10% of the total treated flow through the DWTP	Control rate of return of recycled water to head of DWTP to keep below a set percentage of the total flow through the DWTP Ensure minimum quality in recycled water (i.e. turbidity, residual metals)
Membrane filtration – fouling causing blockage and bypass of filters	Membrane filters have been inadequately cleaned and integrity of units has been compromised	Replace membrane modules and implement new cleaning regime with review of air integrity results

2.6 Applications of Filtration Technologies

Filtration processes are one of the key control measures used to mitigate hazards identified in the drinking water safety planning process. The most common applications of filtration processes in drinking water treatment are identified in Table 2.2. This should not be considered an exhaustive list. A single technology can be applied to multiple applications, and alternative treatment processes (e.g. coagulation and clarification) may also be appropriate.

Table 2.2: Common filtration applications

Application	Definition	Examples
Pre-treatment	Filtration process used to ensure sufficient water quality, usually with respect to the reduction of particulate matter and turbidity, to protect the integrity of downstream processes	Cartridge filter upstream of UV disinfection Roughing filter containing coarse sand media to reduce turbidity often in highly turbid or variable river sources
Pathogen removal	Filtration process used to reduce numbers of potentially pathogenic organisms by providing a physical barrier and removal of pathogens from water	Membrane filtration Rapid gravity filter downstream of coagulation and clarification

Application	Definition	Examples
Metals removal	Filtration process used to remove metals. Occasionally preceded by addition of chemical oxidation, or pH adjustment (NaOH or lime, most commonly), to precipitate metals upstream of filtration	Rapid gravity filter with chlorine dose applied upstream Second stage media filter, operated at high (alkali) pH
Reduction of TOC and DBP precursors	Removal of soluble TOC and other DBP precursors by adsorption mechanism	GAC
Removal of micropollutants	Removal of soluble compounds through adsorption	GAC
Treatment of process residuals	A filtration process used to provide treatment to process residual stream to either achieve solids separation or ensure quality for any recycle of liquid residuals to head of DWTP	Cartridge filter on liquid recycle to head of DWTP

Table 2.3 presents examples of source water and DWTP hazards that can be mitigated with filtration processes. For each hazard, a required control measure is proposed along with a potential type of filtration process that can be used as a mitigation measure. This table provides examples only and should not be taken as exhaustive.

Table 2.3: Filtration processes as control measures for DWSP hazards

Hazard	Required control measure	Filtration Objective(s)	Treatment process
Cryptosporidium in source water entering water treatment plant	Provide removal of *Cryptosporidium* (log reduction credits)	Turbidity reduction Pathogen removal	RGF with upstream coagulation, flocculation and clarification (CFC)
Pesticides in source water exceed allowable limit	Install media to adsorb target pesticide to ensure compliance	Organics reduction	GAC
Turbidity in abstracted groundwater > 0.2 NTU	Reduce turbidity to < 0.2 NTU as required for downstream UV disinfection.	Pre-treatment	Cartridge filter
Cryptosporidium in settled backwash water or process water residual treatment returned to head of DWTP	Provide for reduction/removal of same	Residual treatment	Cartridge filtration or UV treatment.

2.7 Log Reduction Credits

2.7.1 Background and outline of approach

One of the main objectives of drinking water treatment is to reduce the number of pathogenic organisms in water supplied for human consumption. Because it is not possible to rapidly detect the presence of many waterborne pathogenic organisms, such as *Cryptosporidium*, in water, a "log credit" approach has been developed to quantify the capacity of a treatment process to decrease their numbers. The log credit approach has been implemented across several international regulatory jurisdictions

Log credits apply to both the physical removal of a pathogenic organism from the treated water (i.e. filtration) and the inactivation of pathogenic organisms (i.e. disinfection by ultraviolet disinfection, chlorination and ozone). Inactivation renders the organism dead or no longer able to reproduce. The greater the number of log credits granted to a treatment process, the larger the percentage of protozoal entities, such as oocysts, the process is able to remove and/or inactivate. Treatment plants often have more than one treatment process that can remove or inactivate pathogenic organisms. Log credits from each process can be added to determine the theoretical overall log removal for the plant.

To determine whether the number of log credits achieved by a particular treatment plant is sufficient, the water supplier needs to identify the log requirement, usually a deficit, associated with the source water. This can be achieved by ascertaining the average concentration of Cryptosporidium in the source water through monitoring, or, where inadequate monitoring is available, by developing a source classification scheme with an associated log requirement for each category. Both methods deliver a risk assessment of the source water. Water suppliers should strive to have treatment in place at each DWTP that exceeds the minimum log reduction/inactivation deemed necessary by the source water risk assessment.

The logarithmic scale provides an effective way to demonstrate changes where there is a large difference in the numbers being compared. The scale expresses a decrease in numbers by factors of 10; in this context, the decrease in question is in the number of pathogenic organisms. The logarithmic scale is readily converted to percentage removal as shown in Table 2.4.

Table 2.4: Percentage of removal and log reduction credits

% removal	Log reduction credit
90	1
99	2
99.9	3
99.99	4

Example calculations of how to determine log removal, comparing organism concentrations in raw (influent) and filtered (outlet) water, are provided in Appendix B.

The log credit concept has been used by the US EPA since the implementation of the 1989 Surface Water Treatment Rule. It is set out in the US EPA's *Long Term 2 Enhanced Surface Water Treatment Rule Guidance Toolbox* (US EPA, 2010). The New Zealand Ministry of Health (2017) *Guidelines for Drinking Water Quality Management for New Zealand* present guidance on the approach, which is heavily based on the US EPA's approach and incorporates international best practice. The WHO provides a general overview of log credits for core water treatment processes from source abstraction to chemical disinfection (WHO, 2017a). The New Zealand guidelines are referenced throughout this water treatment manual on filtration as they have been most recently updated and incorporate the drinking water safety plan approach.

The log credit approach is not currently a regulatory requirement in Ireland. However, it is a valuable tool to use in drinking water safety planning control measures.

This document does not provide guidance on the identification of log deficits associated with different source water types but does provide guidance on the operational requirements to be met when the log credit approach is adopted.

An example of the log removal credits for *Cryptosporidium* at a conventional water treatment plant with coagulation, flocculation, settlement clarifiers (CFC), filters and UV disinfection with chlorine contact is as follows:

CFC and filtration	= 3 log removal
UV disinfection	= 3 log inactivation (full validated UV dose)
Chlorine disinfection	= 0 log removal (*Cryptosporidium* not inactivated by chlorine)
Total	= 6 log reduction (99.9999% reduction in *Cryptosporidium*)

2.7.2 Target organisms considered by the log credit approach

Log credits are typically applied to three target organisms:

- ***Cryptosporidium* oocysts**: the "oocyst" life cycle stage of this protozoan (typically 3–6 µm) is not susceptible to inactivation by chlorine. Reduction in concentration by filtration often followed by inactivation technologies (i.e. ozone, UV) is generally practised.
- ***Giardia***: the "cyst" life cycle stage of this protozoan (typically 9–14 µm) is hardy but, with sufficient targeted dose, is vulnerable to chlorine disinfection with sufficient chlorine contact time. These cysts can be removed by filtration, chlorine disinfection and/or alternative disinfection processes.
- **Viruses**: small, infectious organisms (typically < 0.1 µm) that replicate only inside the living cells of an organism. Some removal of viruses is achieved by conventional media filters. Most viruses are susceptible to chlorine disinfection. Some strains can be resistant to UV disinfection.

The *Cryptosporidium* oocysts and *Giardia* cysts life cycle stages represent the dormant or resting phase of the organism. These life cycle stages are specifically targeted for removal by filtration processes as they represent the most disinfection-resistant form of the pathogen. Targeting this life cycle stage will ensure that all forms of the organisms are removed and/or inactivated effectively. *Cryptosporidium*, being the smallest pathogenic protozoan (it can reach 15 µm in size but 3–6 µm is most typical), is the most difficult to consistently remove by filtration. Designing filtration processes for *Cryptosporidium* removal is, therefore, the most conservative approach.

There is no log credit considered for bacteria. However, bacteria are taken into account as the chemical disinfection and inactivation requirements for viral and protozoal inactivation are in excess of requirements for bacterial inactivation. Therefore, ensuring sufficient log removal of the three target organisms should achieve effective disinfection against all currently known waterborne pathogenic organisms.

There is one notable difference between the US EPA approach and that of the New Zealand Ministry of Health. The US regulations apply separate log credits to *Giardia* and *Cryptosporidium*, whereas the New Zealand guidance applies the log credit approach only to protozoa, but utilises *Cryptosporidium* as the reference organism. The different approaches are compared in Table 2.5. In both the US EPA and New Zealand jurisdictions, the required log reduction is linked to the occurrence and detection of *Cryptosporidium* oocysts in the source water.

Table 2.5: Comparison of log credit requirements

	Regulating body	
	US EPA	**New Zealand Ministry of Health**
Reference regulation	Long Term 2 Extended Surface Water Treatment Rule (2003) Log Removal Requirements for DWTP with Filtration	*Drinking-Water Standards for New Zealand 2005* (Revised 2018)
Log credit requirements	Virus: 4 log *Giardia*: 3 log *Cryptosporidium*: 2–5.5 log	Protozoa: 3–4 log

2.7.3 Log reduction for filtration processes

For each core filtration technology discussed in this manual, an outline of the log credits achievable for *Cryptosporidium* removal and any relevant associated performance criteria are provided. All guidance provided is based on the current New Zealand Ministry of Health (2017) *Guidelines for Drinking-Water Quality Management*. Table 2.6 provides examples of filtration processes and their log removal potential.

Table 2.6: Example log removal credits for Cryptosporidium (WHO, 2009)

Process type	Log removal	Critical qualifying factors
Microstrainers	0	Mesh too wide for removal of pathogens
Conventional filtration (as defined in section 2.2)	3.0	Coagulation dose, clarification performance, filter integrity
Direct filtration	2.5	Filter integrity, coagulant dosed
Slow sand filtration	2.5	Filter depth, filtration rate, presence of *schmutzdecke*, temperature
Membrane filtration	> 4	System integrity. Log credit determined by manufacturer during independent challenge testing

It is important to note that log credits are not typically given to media-based filtration processes in which a coagulant is not dosed upstream. This is because coagulation is an integral part of the barrier to pathogens and the effectiveness of the process is less certain without the upstream chemical dosing. However, log credits are given to some filtration processes without upstream coagulation, including alternative filter media, cartridge filters, pre-coat filtration and slow sand filtration. Further details on log credits are available in the individual chapters covering the technologies referenced above.

Guidance on the performance criteria that apply when the log credit approach is employed is provided in Chapter 3.

3. CONTROL AND OPERATION OF FILTRATION PROCESSES

3.1 Critical Control Parameters

For all filtration technologies there are parameters and/or operations that need to be monitored and/or verified to ensure the integrity of the treatment process. Further, under the DWSP approach to the management of supplies, control measures applicable to filtration may include the need for online instrumentation, associated alarm set points, an automated shutdown of a process unit or the entire drinking water treatment plant (DWTP). Some control measures require verification through operational tasks and on-site testing.

For each core technology addressed in this manual, a table of critical control parameters has been presented. These tables provide a list of suggested parameters that require a control measure to ensure a hazard or risk does not materialise. Types of controls include:

- an operational procedure to ensure sufficient response to a pre-set trigger,
- online continuous monitoring with configured alarms,
- automatic shut-down of water treatment process unit and/or water treatment plant,
- on-site testing,
- Operational tasks to verify asset condition and performance.

Guidance is provided in sections 3.2 to 3.4 on approaches to verifying filtration processes.

3.2 Verifying Filtration Performance

Process verification is an important part of the drinking water safety planning methodology. Generally, water treatment processes are verified in one or both of the following ways:

1. **Process monitoring**: a parameter is routinely and/or continually monitored to verify a substance. The parameter monitored can be the targeted water quality parameter, or a surrogate parameter can be used:
   - continuous turbidity monitoring (i.e. monitoring of turbidity from filters);
   - indirect verification by monitoring of a surrogate parameter (E.g. measurement and/or control of flow rate through a GAC adsorber to maintain empty bed contact time (EBCT) above minimum allowable time).
2. **Integrity testing**: the process is monitored or tested to confirm that there are no potential integrity issues with the filter matrix (i.e. there has been no damage to the physical structure of the membrane that will have an impact on performance). Integrity testing can be direct or indirect:
   - **Direct integrity testing**: the filter matrix is subjected to testing to confirm that the integrity of the filter has not been compromised (e.g. air integrity testing of membranes).
   - **Indirect integrity testing**: parameters are monitored which, when exceeded, are likely to indicate an issue with integrity of the filter matrix (e.g. differential pressure monitoring for cartridge filters).

Each treatment process requires the establishment of performance criteria specific to its objectives. If a process has multiple treatment objectives, criteria should be identified for each. Table 3.1 provides examples of filtration objectives with associated performance criteria and methods of verification.

Table 3.1: Example process performance criteria

Treatment process	Filtration objective	Performance criteria	Method of verification
RGF/slow sand filtration	Provide removal of *Cryptosporidium* (log removal credits)	Filtered water turbidity maintained below the required limit	**Direct monitoring**: continuous monitoring of filtered water turbidity
GAC	Filter media adsorbs target pesticide to ensure that its concentration in filtered water is below the parametric value	Pesticide below parametric value	**Surrogate monitoring**: confirm EBCT is maintained
Cartridge filter	Provide protection of downstream treatment process	Effective barrier remains intact	**Indirect integrity**: continuous monitoring of head loss
Ultrafiltration process	Provide removal of *Cryptosporidium* (log removal credits)	Confirm integrity of filtration barrier	**Direct integrity testing**: complete air integrity test every 24 hours

Performance criteria specific to each filtration technology are presented in the individual technology chapters (Chapters 4–9).

3.3 Verifying the Performance of Protozoa Barriers

Where a filtration process is in place to provide a barrier against protozoa (e.g. *Cryptosporidium*), specific consideration must be given to the establishment of performance criteria to verify that the installed treatment barrier is satisfactory. The performance criteria selected depend on the source water challenge, the on-site treatment and the selected treatment technology(s). The performance criteria will then be validated through integrity testing and process monitoring.

There are two options for establishing performance criteria for filters used as a treatment barrier for protozoa:

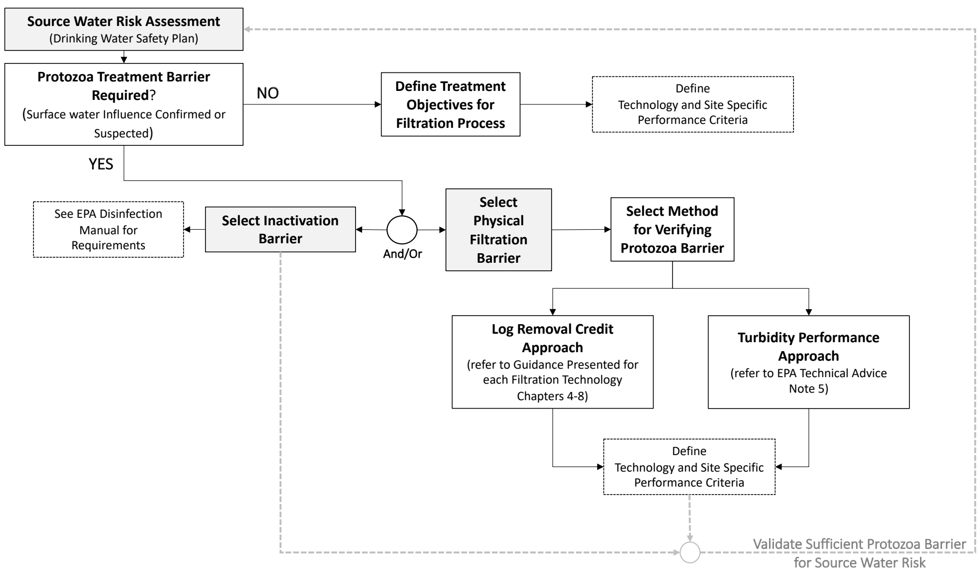
1. **Turbidity performance approach**: water treatment operators will apply the requirements outlined in the *EPA Advice Note on Turbidity in Drinking Water* (EPA, 2009), which requires turbidity to be maintained below 0.2 NTU. This provides an adequate *Cryptosporidium* barrier.
2. **Log removal credit approach**: adopt the log removal credit approach as outlined in section 2.7. Where a filtration technology is eligible for log removal credits, the basic requirements are outlined in this document.

The approach used will depend on the selected filtration technology and its defined treatment objectives. For example, water utilities operating conventional RGF or slow sand filtration can select either the turbidity performance or the log removal credit approach. The methodology that outlines the selection of either approach to validate a protozoa barrier is outlined in Figure 3.1.

Where the log removal credit approach is adopted, some DWTPs will require an additional barrier downstream of filtration to achieve sufficient log removal/inactivation, depending on the source water's log removal/inactivation requirements.. Because adoption of the log credit approach will often prescribe an additional barrier downstream of filtration, operational limits for turbidity can be higher than the limits required for filters verified by the turbidity performance approach (e.g. 0.5 NTU, compared with 0.2 NTU for slow sand filtration).

When there is an option to apply the log removal credit approach to a specific filtration technology, the basic criteria and turbidity performance criteria have been outlined (in Chapters 4–8), side by side with those applicable to the turbidity approach for that technology. All the criteria outlined should be adopted and appropriate validation methods must be determined for each.

Figure 3.1: Decision tree for verifying protozoa barrier for filtration processes



3.4 Guidance for Continuous Online Monitoring of Turbidity

Recent decades have seen major advancements in data capture capability and telemetry available to DWTPs. Modern water treatment plants can record turbidity readings at frequencies of less than a second. It is important to consider and clearly define the maximum turbidity reading interval allowable before elevated turbidity is considered an "event", while balancing the need to avoid nuisance and false alarms to plant operators and alarm responders. Further guidance on appropriate turbidity alarms is provided in the *EPA Advice Note on Turbidity in Drinking Water* (EPA, 2009).

It is recommended that turbidity should be monitored continuously after each individual filter and on the combined filtered water where more than one filter is in place. Each technology chapter identifies critical control monitoring points specific to each process that should be implemented (e.g. feed water, individual filters). The *EPA Advice Note on Turbidity in Drinking Water* (EPA, 2009) provides guidance on appropriate monitor extraction points, cleaning and calibration.

3.4.1 Minimum monitoring frequency

The following guidance is provided for filtration processes that provide a *Cryptosporidium* barrier and/or are the final turbidity barrier before downstream disinfection processes (i.e. ultraviolet disinfection, chlorine disinfection):

- Turbidity should be recorded at a minimum frequency of **every minute**. Water quality instrument installation should allow for the minimum monitoring frequency to be achieved.
- Consideration must be given to the **analysis loop time**. The time taken to supply a fresh sample plus the time required for sample analysis must be less than the data recording frequency. This is particularly relevant to sites with long sample lines between the point of sampling and the instrument.
- The **recording frequency** should not be less than the instrument loop time.
- Water treatment plants should maintain **records** for all instrumentation with sample line length and estimated loop time.

3.4.2 Definition of operational targets

For each water quality or process monitoring parameter, there are often multiple targets set. To achieve 100% compliance with a regulatory limit (e.g. maximum allowable turbidity of 1 NTU prior to disinfection), DWTPs should establish lower operational targets.

Each type of target requires a set “duration” to define when the target will be considered breached. Therefore, it is important to specify both the maximum allowable parameter value and the time duration. Specific guidance that applies to the limits given in the technology specific guidance is outlined in section 3.4.3 as it applies to all the technology-specific chapters (Chapters 4–9).

Both operational target types, when exceeded, will trigger an event. This is outlined further in section 3.4.3 below. The recommended targets are summarised in Table 3.2.

Table 3.2: Types of targets and limits for water quality parameters

Target type	Description	Example action	Event type	Example trigger for event
Regulatory limit	Exceeds the maximum permissible water quality value.	Shut down DWTP until corrective action can be applied	Regulatory event	Turbidity post filter is > 1.0 NTU for 3 minutes
Operational upper limit (high alarm)	Maximum allowable value selected by DTWP operational team. Treatment integrity will be compromised if not rectified. Immediate corrective action required	Consider shutdown of treatment unit(s)	Operational event	Turbidity post filter is > 0.5 NTU for 15 minutes
Operational limit (alarm)	Trigger for requiring rapid operational action	Immediate operational response as per documented alarm response procedures	None. Operational log book is sufficient	> 0.3 NTU for 15 minutes
Performance target	Performance target. Exceedances should trigger action or review of root cause	Operator response or process audit	None. Operational log book is sufficient	> 0.1 NTU

It is expected that alarms should be set for both operational limits (alarm and high alarm) in addition to the operational event. The performance target should be monitored as part of the DWTP operational logs and operational procedures (i.e. triggering a process audit, maintenance event or other investigations as required).

It is also expected that any exceedance of any of the above targets or limits will be sufficiently documented in the on-site operational log book.

3.4.3 Definition of an event

In the context of post-filtration water quality, an event is defined as confirmation of turbidity above the allowable limit at which operational response is required. Two classes of events are defined below and summarised in Table 3.3.

1. **Regulatory event**: turbidity exceeds the maximum turbidity of 1 NTU allowable by the EU Drinking Water Regulations and current regulatory guidance. A regulatory event is defined as the occurrence of **three or more consecutive** turbidity readings (meeting minimum monitoring frequency of every minute) above the allowable threshold. Operation of a DWTP above the regulatory limit will result in inadequately treated drinking water being provided to the supply. In these instances, immediate intervention and/or shutdown is required.
2. **Operational event**: turbidity exceeds the maximum operational limit allowable as defined by regulatory guidance and water treatment plant procedures. An operational event is defined as the occurrence of **15 or more consecutive** turbidity readings (meeting minimum monitoring frequency of every minute) above the established limit.

Corrective action should be taken if the operational limit is exceeded, with consideration given to process unit shutdown. While it is expected that, occasionally, some DWTPs may operate above the operational limit when source water quality challenges the plant outside its design tolerance (e.g. during extreme weather, drought conditions or algal blooms), such occurrences should prompt close observation by the operator with a readiness for intervention and corrective action.

All processes should have an operational event threshold and alert mechanism which is lower than that of the regulatory event to allow for a suitable operational response. It is important to note that all events should also be documented in operational log books.

Table 3.3: Definition of an event for filtration process used as Cryptosporidium barrier

Type of event	Applies	Limit	Definition of event	Response
Regulatory event	All DWTP	1 NTU	3 or more consecutive readings	Immediate response and/or shutdown followed by appropriate investigation and intervention
Operational event	DWTP using turbidity approach	0.2 NTU	15 or more consecutive readings	Appropriate operational intervention and investigation. Corrective action to be taken or process unit shutdown considered
	DWTP using log credit approach	Varies as per specific treatment process guidance	15 or more consecutive readings	

3.5 Requirement for Treatment Process Standard Operating Procedures

The EPA's Handbooks for Implementation of the European Communities Drinking Water Regulations (EPA, 2010a,b) provide guidance for quality management processes. A core requirement to achieve this is to have standard operating procedures (SOPs) that set out how each part of the process and other related matters are to be operated and maintained at each treatment works so that the water leaving the treatment works meets the standards and other requirements of the regulations. These include:

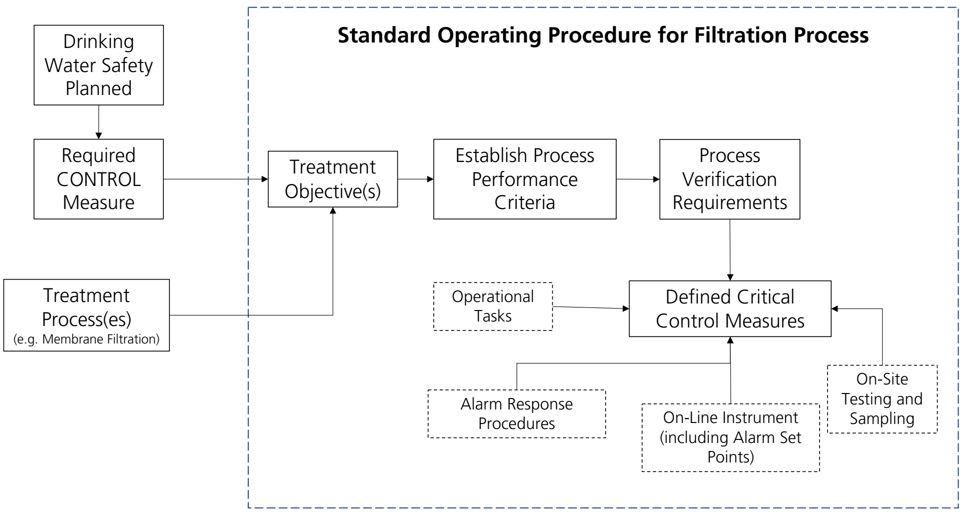
- operational activities required for normal operations and abnormal conditions;
- response to unusual or abnormal circumstances;
- criteria that describe the satisfactory operation of the process (i.e. process performance goals and critical control parameters), including monitoring and sampling requirements;
- defined warning levels for when process performance is deteriorating, including alarm levels;
- required operational tasks and activities with required frequency.

The information in this manual has been structured to provide guidance to prepare a detailed SOP. All core filtration processes that have been identified in Ireland have been presented as stand-alone chapters. The content of each chapter addresses:

- basic process overview;
- guidance for process objectives and requirements for log removal credits;
- outline of process equipment;
- review of basic design considerations;
- guidance for operation of treatment process;
- minimum recommended critical control parameters and recommended operational tasks;
- review of upstream and downstream process considerations;
- specific guidance for process start-up and shutdown;
- advantages and disadvantages of treatment process.
- An example SOP template has been provided in Appendix C.

Figure 3.2 provides the recommended methodology for integrating the development of treatment process SOPs with the hazards and required control measures identified in the DWSP process. Where a protozoa barrier is required, the method of verification should be selected as per the information provided in section 3.3.

Figure 3.2: Example methodology for establishing effective SOPs for treatment processes.

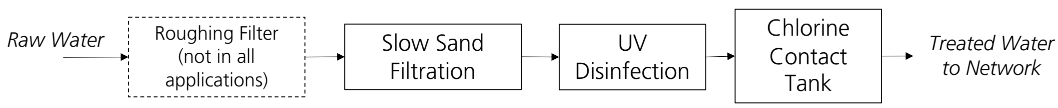


4. SLOW SAND FILTRATION

4.1 Process Overview

Slow sand filtration (SSF) refers to the treatment process in which water flows downwards through a bed of sand at a slow velocity, typically at rates of < 0.3 m/h. The technology has had long-standing applications since the early 1800s, with installation at major European cities including London predating the early 1900s. Coagulants are not typically dosed upstream of slow sand filtration applications; however, some applications may have a coarser filter upstream (e.g. roughing filter). An example of a typical DWTP using slow sand filtration is outlined in Figure 4.1.

Figure 4.1: Example of a slow sand filtration DWTP.



Given the larger footprint required for slow sand filtration, it has decreased in popularity compared with conventional filtration plants. Two additional disadvantages are sensitivity to colder temperatures and the fact that turbidity performance is generally lower.

The mechanisms involved in slow sand filtration include adsorption and straining (refer to Chapter 2). In addition to these physical filtration mechanisms, a complex combination of biological processes dominates in slow sand filtration performance.

The general process overview is as follows.

Filter ripening: when a new (virgin media) or cleaned filter is brought into use, a *schmutzdecke* (literally translating as "layer of dirt"), consisting of bacteria, algae, protozoa and colloidal matter derived from the raw water, develops on the top of the filter bed after a number of days' operation. Filter ripening can take up to 2 weeks, depending on temperature and the amount of virgin media in the filter.

Filtration: once ripening has been completed, biological processes in the slow sand filter provide three distinct zones:

- **The *schmutzdecke*:** much of the treatment process takes place in this layer, with suspended and dissolved matter including microorganisms removed by physical and biological action.
- **Autotrophic zone:** forms just a few millimetres below the *schmutzdecke*. Biological activity in this layer consumes available organic matter and any available nitrogen, phosphates and carbon dioxide while producing oxygen.
- **Heterotrophic zone:** this zone extends some 300 mm into the filter media bed. Bacteria are present in large populations and consume any available organic matter. These not only break down organic matter but also destroy each other and so tend to maintain a balance of life native to the filter so that the resulting filtrate quality is uniform.

The remaining sand bed provides further water purification by an adsorption and straining mechanism. Over time the pores within the filter bed will become clogged, increasing head loss across the filter bed. To overcome this, the depth of the water must be increased above the filter bed to maintain filter throughput. It typically takes several hours for water to pass through the sand bed.

Cleaning/scraping: when the maximum recommended head loss has been obtained, the sand filter must be manually cleaned. This involves draining the filter and removing the top 10–30 mm of the sand where the larger particles and *schmutzdecke* have accumulated. Figure 4.2 illustrates one approach to the completion of scraping. An alternative to the traditional slow sand filter that allows for backwashing has been developed. Further details about this technology are provided in Chapter 10.

Re-sanding: as a small amount of the sand media is removed each time the filter is cleaned/scraped, media top-up and/or replacement will be required throughout the life of the slow sand filter. A well-designed slow sand filter will probably need to be re-sanded every 2–5 years, typically when the bed reaches the minimum allowable depth, which is recommended to be 0.6 m.

Figure 4.2: Example of a slow sand filter during cleaning/scraping.

4.1.1 Filtration objectives

Slow sand filters are typically used for the following filtration objectives:

- **Pathogen removal**: slow sand filtration can provide effective removal of protozoa and other harmful organisms.
- **Turbidity reduction**: slow sand filtration can provide effective removal of solids.
- **Organic reduction**: slow sand filters also provide removal of general suspended solids and limited reduction of TOC and colour.

The *EPA Advice Note on Turbidity in Drinking Water* (EPA, 2009) recommends a filtered water turbidity target of < 0.2 NTU when filters are being used as a *Cryptosporidium* barrier. This target can often be achieved by slow sand filters; however, some filters may struggle in colder winter temperatures due to limitations on the biological activity.

Removal of colour (measured using the Hazen scale) associated with organics and humic acids in the raw water can be expected to occur in a fully ripened bed. Experience indicates that TOC removal as a result of slow sand filtration is less than would be expected in a conventional treatment plant, which means that there is a potentially higher risk of DBP formation from slow sand processes. Slow sand filtration is not a suitable selection for new water treatment plant installations if the source water TOC levels are > 2.5 mg/l.

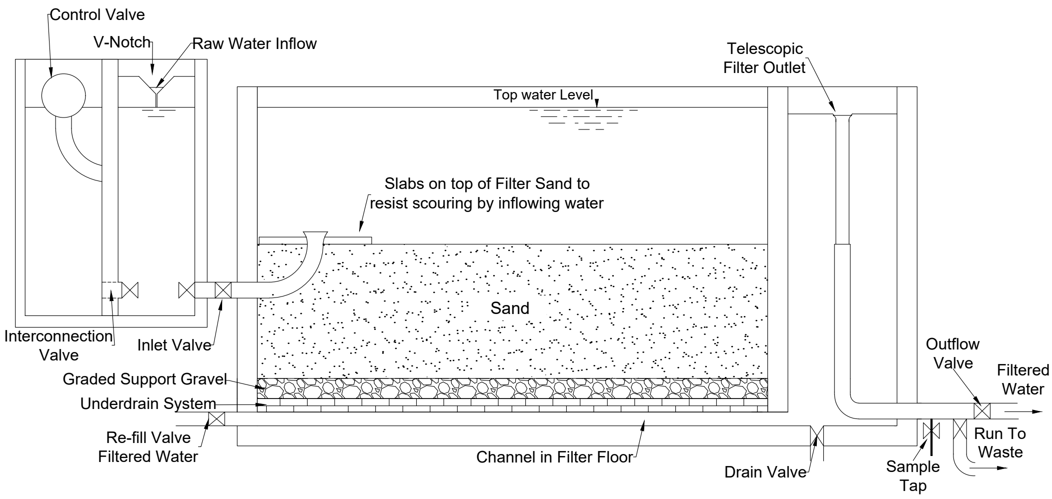
4.2 Process Equipment and Layout

A slow sand filtration system will typically have the following elements:

- **Filter shell**: the structure that holds the filter media bed and underdrainage collection system. This is most commonly concrete. The shell has to be adequately sized to allow for the changing water level required above the sand bed as the filter becomes clogged from use.
- **Filter underdrain system**: this provides for an even collection of the filtered water from the bottom of the media bed to a central collector channel. Such systems are generally constructed from perforated pipes. However, proprietary systems including perforated floors and narrow-slit nozzles are sometimes used.
- **Media bed depth**: the target media bed depth will typically be 0.9– 1.25 metres (m), with a minimum recommended operating depth of 0.6 m. The minimum design depth should not be < 0.9 m. The bed will be supported by a layer of gravel, the depth of which is typically at least 0.2–0.3 m but depends on the requirements of the underdrain system. Some filters may also include for a layer of activated carbon (typically 100–150 mm deep) as the top layer of the filter bed. A level marker should be provided to allow the sand depth to be easily read by operational teams.
- **Valves**: each filter will require five valves:
  - inlet – must discharge water at a rate that will not damage the *schmutzdecke*;
  - outlet – allows filtered water to pass forward;
  - back-filling – used to refill the filter after cleaning/scraping or re-sanding;
  - waste – used to discharge the filtrate until the ripening process has been completed;
  - drain – used to remove the top water from the filter to allow for cleaning and inspection.

A cross-sectional view of a typical SSF is provided in Figure 4.3.

Figure 4.3: Overview of slow sand filter.



4.2.1 Considerations for filter media

Slow sand filter media generally consists of silica sand. The effective size (ES) is typically 0.15– 0.4 mm, with a uniformity coefficient (UC) of < 2 considered optimal.

Historically, it was considered that TOC and colour reduction can be enhanced by the provision of a GAC layer at the top of the sand bed, which could be retrofitted into the media bed when the sand was replaced. This was generally found to be unsuccessful as the GAC layer was typically exhausted, often within several weeks of installation.

4.3 Design Considerations

The following water quality parameters are recommended for the source and/or feed water to a slow sand filtration process:

- turbidity: < 10 NTU;
- TOC: < 2.5 mg/l;
- chlorophyll a: < 0.05 µg/l;
- iron: < 0.3 mg/l;
- manganese: < 0.05 mg/l.

The following design parameters are critical to consider for slow sand filters:

- **Filtration rate (m/h)**: the rate at which water passes through the media bed as reflected by filtered flow (m^3/h)/ per unit surface area of the filter (m^2). The exact figure will be site specific, but generally rates in excess of 0.3 m/h are considered inappropriate when protozoa removal is targeted. Older designs in Ireland typically used a more conservative design rate of 0.1–0.2 m/h.
- **Process redundancy**: the design must ensure that there is sufficient filter capacity (number of filters and available surface area of filtration media) that the maximum allowable filtration rate is not exceeded when filters are out of use for repair, cleaning or re-sanding.

- **Media bed depth**: in slow sand filters the design depth is typically within the range 0.9– 1.2 m considering that the bed depth will gradually decrease as a result of cleaning requirements.
- **Aeration**: the water may become anoxic as it travels through the filter bed. A method for aeration should be installed to restore dissolved oxygen and remove any dissolved carbon dioxide. This is typically achieved by having an outlet weir that drops water at least 1 m vertically. The weir structure will be at the same level as the sand surface. It will have a secondary benefit of ensuring that the water level in the filter does not drop below that of the sand. Organisms in the surface layer need a steady supply of food and oxygen. The biofilm in the *schmutzdecke* will be negatively impacted if it not continually wetted.
- **Flow control**: it is imperative that the filter bed remains submerged at all times. To eliminate the risk of the water level dropping below the bed, there is usually a weir installed on the filter outlet pipework. To ensure that filters are loaded evenly, a splitter weir or adjustable bellmouth is typically provided.
- **Point of application of disinfectants**: owing to the biological processes involved with slow sand filtration, any chemical disinfectant must be dosed downstream of the filter.
- **Covers for cold weather protection**: where there is a risk of exposure to cold temperatures and the water temperature dropping below 6 °C, covers should be considered. Water temperature affects the metabolic rate of the biofilm in the *schmutzdecke* and hence the removal of microbial contaminants.

4.4 Guidance on Operation

4.4.1 Ripening

During the filter ripening period, the water should not be supplied into the distribution network. The filtered water must be either run to waste or recirculated to the head of the works. The length of time required for filter ripening is dependent on numerous factors, with temperature and the amount of virgin media present in the filter bed being two of the dominant influences. The ripening period for a filter being returned to service after cleaning could be as short as a few days, whereas 1–2 weeks may be required for brand-new media bed in cooler temperatures. Turbidity is the predominant water quality parameter used to confirm that the ripening process has been completed. Coliforms can also be used, with a recommended target of < 1 colony-forming units (CFU) per 100 ml recommended; however, given the required turnaround time for the coliform plate counts, this is often not practicable.

4.4.2 Filtration

One key parameter to monitor during the filtration stage is the head loss across the filter bed. The head loss is allowed to increase to achieve a constant outlet flow rate from the filter. It is recommended to remove the filter from service for cleaning when the water height above the top of the bed reaches a value between 0.6 and 1.2 m (generally 0.9 m). As an example, a clean bed operating at loading rates of 0.1–0.2 m/h would typically have head loss across the filtration bed of approximately 75 mm.

The length of the filter run is mostly dependent on the quality of the raw water being treated, the water temperature (i.e. seasonal conditions) and the loading rate. While summer conditions promote rapid development of the *schmutzdecke*, they also encourage the growth of algae on the filter, which negatively impacts on filter run times. High suspended solids in the raw water, which would typically occur in winter conditions, also negatively impact on filter run times. Filter run times of up to 3 months can be achieved in ideal conditions. However, filter runs can be as low as a matter of days when the raw water is drawn directly from a flashy river directly onto the filter without intermediate settlement. In general, average filter run rates of 25–30 days should be achievable for water of average turbidity of ≤ 10 NTU drawn from an impoundment or lake.

4.4.3 Cleaning/scraping

When the maximum recommended head is observed, the slow sand filter is removed from use for cleaning/scraping. The expected frequency of cleaning/scraping is very dependent on the source water quality. In some installations there will be months between cleaning/scraping requirements. Where there is no upstream pre-treatment and/or algae challenges cleaning/scraping can be required every 1–2 weeks. The required steps are outlined as follows:

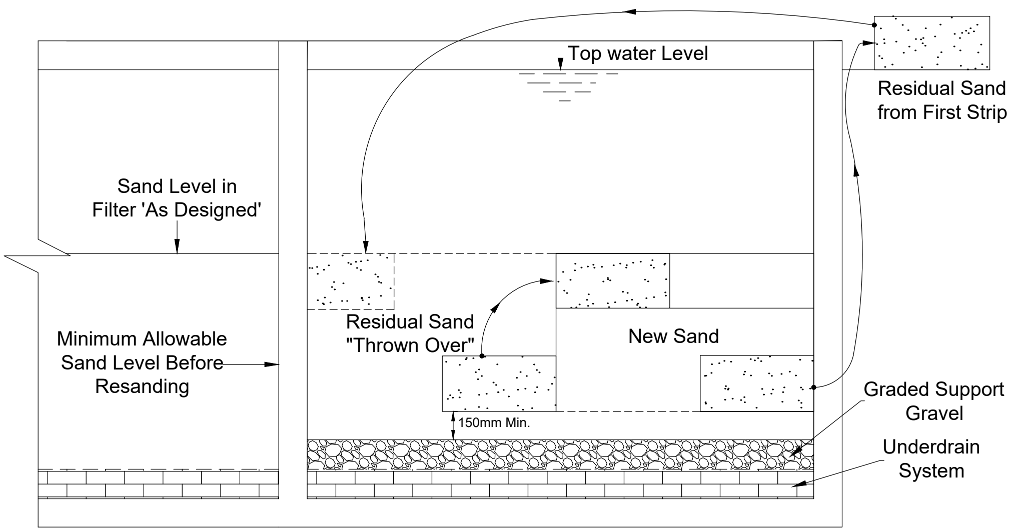
- **Drain-down**: the filter is removed from service and drained into the supply. This can take several hours and is often left to take place overnight. Alternatively, the outlet valve can be closed, and the remaining water drained to waste until the water level is 100 mm below the surface of the sand bed.
- **Cleaning/scraping**: cleaning is completed by scraping the filter media bed, which can be done as soon as the *schmutzdecke* layer is sufficiently dry while still moist. If the layer is allowed to dry out, it can be more challenging to remove it. Traditionally, scraping was completed manually; however, mechanical equipment is used in more modern installations. It can be challenging to retrofit the use of newer mechanical equipment in older installations.
- The scrapings removed from the filter can be washed for re-use or sent off-site for disposal. A total of 10–30 mm should be removed from the filter bed each time the filter is cleaned/scraped.
- After cleaning/scraping, the bed should be smoothed to restore a level surface and the walls below the normal top water level should be cleaned to discourage any biological growth (i.e. algae). Ideally, the filter bed should be returned to service before it dries out, to conserve the biomass remaining in the bed. This will reduce the time required for re-ripening of the filter bed.
- **Refill** and **run to waste**: it is common to refill the filter by allowing water to backflow through the underdrain system until there is a sufficient depth of water above the sand surface to prevent any disturbance of the bed from the inlet flow to the filter. This also minimises the risk that air will be entrapped with the filter media bed, which can interfere with the biological and physical filtration mechanisms.

The flow rate will be slowly incremented through the filter as it is run to waste (or recycled to the head of the DWTP). This will be required for a minimum of several days until the filter ripening process (section 4.4.1) has been completed and the filtered water quality is meeting the DWTP objectives.

4.4.4 Re-sanding

A well-designed slow sand filter will probably need to be re-sanded every 2–5 years, typically when the bed reaches the minimum allowable depth, which is recommended to be 0.6 m. This is because some penetration into this depth can be expected from raw water impurities and products of biochemical degradation. Failure to remove when re-sanding will eventually lead to increased resistance to flow in this layer. The sand removed from this additional depth should be used to top up the filter to its original depth, thus providing it with an ideal substrate to promote rapid development of the *schmutzdecke* compared with the longer period for this to develop using cleaned or new sand. An overview of the trenching method is demonstrated in Figure 4.4.

Figure 4.4: Cross-section overview of re-sanding a slow sand filter using the trenching method.



4.5 Process Optimisation

It is important to allow for the inevitable need to take slow sand filters out of service for cleaning and eventual re-sanding. While it is important to ensure that no excess surface loading occurs to the filters in service, the situation of having a number of filters reaching their terminal head condition during the same period should be avoided by forward planning. In many plants there are certain times of the year when poor source water quality and/or seasonal demand stretch the filtration capacity. It is advisable to avoid having to clean or re-sand during these periods if possible.

4.6 Critical Control Parameters

The identification of critical control parameters is an important aspect of applying the DWSP methodology. Table 4.1 summarises the recommended critical control parameters and associated control measure for slow sand filtration processes. This list should not be taken as exhaustive, but should be used as guidance as part of the DWSP development for a site.

Table 4.1: Critical control parameters for slow sand filters

Critical control parameter	Significance	Recommended control
Feed water turbidity	It is important to measure the raw water turbidity at the same frequency of the filtered water turbidity to check on its particle removal performance. Filtered water turbidity that is greater than feed water turbidity is also an indication of a potential issue with the biological removal process within the filter	Continuous online turbidity instrumentation
Individual filtered turbidity	Identifies any issue with an individual filter and ensures that any targets for log removal are achieved. Older installations may not have been included for continuous monitors of individual filters but should have a regular operational monitoring programme in place in lieu of these critical instruments	Continuous online turbidity instrumentation
Combined filtered turbidity	Identifies any issue impacting all filters. Required to maintain for downstream disinfection processes (i.e. chlorine disinfection, UV disinfection)	Continuous online turbidity instrumentation
Raw water temperature	The temperature should be measured on a continuous or daily basis. Biological activity within the filter will be impacted at temperatures < 6 °C. In addition, water viscosity increases as temperature decreases, which will lead to an increased head loss across the bed	Continuous or regular on-site test
Filter loading	The loading rate of the filter must be kept below the target, which should be < 0.3 m/h. This requires flow rate monitoring	Continuous flow rate monitoring

Critical control parameter	Significance	Recommended control
Head loss	Head loss will slowly increase over time. Height of water over the top of the bed should not exceed 1.2 m	Continuous online monitoring with water level gauge
Filter media depth	The filter media bed must exceed a minimum of 0.6 m depth at all times	Reference datum or regular depth checks
Water level	Recording the water level is recommended to supplement head loss. Height of water over the top of the bed should not exceed 1.2 m	Continuous online monitoring

4.6.1 Turbidity performance criteria

For slow sand filters to provide a barrier for *Cryptosporidium*, or provide the final turbidity barrier upstream of disinfection processes, the minimum turbidity performance criteria are defined in Table 4.2.

As outlined in Chapter 3, facilities should be designed and operated to achieve performance criteria according to one of the following:

- log credit approach;
- turbidity performance approach;

Table 4.2: Turbidity performance criteria for slow sand filtration

<table>
<tr><th>Type of event</th><th>Applies to</th><th>Limit</th><th>Definition of event</th><th>Response</th></tr>
<tr><td>Regulatory event</td><td>All DWTP</td><td>1 NTU</td><td>≥ 3 consecutive readings</td><td>Immediate response and/or shutdown followed by appropriate investigation and intervention</td></tr>
<tr><td rowspan="2">Operational event</td><td>DWTP using log credit approach</td><td>0.5 NTU</td><td>≥ 15 consecutive readings</td><td rowspan="2">Appropriate operational intervention and investigation.
Corrective action to be taken or process unit shutdown considered</td></tr>
<tr><td>DWTP using turbidity approach</td><td>0.2 NTU</td><td>≥ 15 consecutive readings</td></tr>
</table>

4.6.2 Guidance on log-removal credits

Slow sand filtration is eligible for a 2.5 log credit for protozoa reduction. At facilities where the log credit approach is being applied the following must be achieved as a minimum:

- All water must pass through the filter, and the filter must remain wetted at all times.

- No chemicals providing an effective disinfectant residual can be dosed upstream of the filters.
- Continuous turbidity monitoring is required for each individual filter and total combined filtered water.
- Following maintenance, no filtered water can be delivered to consumers until the filtration process has been demonstrated to be effective.
- The filters are operated at a steady flow rate that does not exceed 0.35 m/h.
- The temperature of the water entering the filter does not drop below 6 °C for > 24 hours.
- The operational limit from any individual filter for turbidity is not to exceed 0.5 NTU for more than 15 consecutive readings.
- The regulatory limit will be exceeded if filtered water turbidity exceeds 1.0 NTU from any individual filter for three consecutive readings.
- Filtered water turbidity from any individual filter should not exceed that of the feed water for any 3-minute period.

4.6.3 Regular operational checks

The operational checks outlined in Table 4.3 are recommended.

Table 4.3: Recommended operational tasks for slow sand processes

Task	Description	Recommended frequency
Visual inspection of *schmutzdecke* layer	Visual inspection of the *schmutzdecke* layer to confirm it appears normal and healthy	Every visit
Visual inspection of media	Inspect the filter media bed. Confirm that the bed is level and no evidence that the sand has bound together or is moving away from the filter walls	Every visit
Media coring	A regular coring of the filter media bed can be useful to monitor the depth of the *schmutzdecke* and confirm the condition of the remaining media bed	Every 4–12 months
Clean filter walls	The filter should be kept clean of any biological growth including algae/ carryover and other biological growths	To be completed with filter cleaning and media refill
Cleaning/scraping	Removal of the *schmutzdecke* by manually cleaning the filter, when the maximum recommended head loss has been obtained	Depends on source water quality, ranges from 1–2 weeks to months
Re-sanding of filter	Replenishment of the filter media to ensure the minimum recommended design depth of 0.6 m sand is present	Every 2–5 years

4.6.4 Operational records

In additional to the monitoring data available from online instrumentation it is advisable to ensure that all operational logs and recorded information as a minimum capture the following information:

- the date of each filter cleaning/scraping event;
- full details of media replacement and disposal/treatment of scraped media;
- the date and hour of return to full service after the filter ripening period, including ambient temperature range;
- the filtration rate;
- raw water, filtered water and final water quality (online instrumentation and on-site testing records) including, as a minimum, turbidity and water temperature;
- details of any incidents, unusual events or notable observations with respect to raw water quality (i.e. algal blooms, storms, etc.);
- the size and key characteristic of media in each filter (e.g. UC, d_{10}, d_{60}, age of installation and any condition or sieving tests completed). Media characteristics are explained in detail in section 5.2.3.

4.7 Upstream and Downstream Considerations

4.7.1 Process inputs

No process inputs are required other than feed water to support a slow sand filtration process.

4.7.2 Process residuals

The following process residuals are produced by a slow sand filtration process:

- **Remove scrapings**: the sand removed during cleaning/scraping events is either cleaned for re-use or disposed of off-site.
- **Run to waste**: waste from the filter run to waste during the ripening period. This is often recycled back to the head of the DWTP.
- **Drain to waste**: during cleaning events, a volume of water must be drained from the filter.

4.7.3 Upstream considerations

Slow sand filtration is often the first inline treatment process for source waters when turbidity is reliably below 10 NTU. However, many slow sand filters are provided downstream of pre-treatment filtration technologies (i.e. roughing filters, micro-screens).

Upstream processes must be optimised to ensure that:

- turbidity is maintained below 10 NTU;
- no chemicals with effective disinfectant residuals are dosed upstream of filter;
- the impact of algae in the source water is minimised.

4.7.4 Downstream considerations

Slow sand filtration is typically installed upstream of inactivation disinfection processes (i.e. chlorine disinfection, ultraviolet disinfection). Alarm response procedures developed for these processes should incorporate considerations for the upstream slow sand filtration, with specific consideration for:

- the ability to restore optimal treatment if upstream disturbance impacts all filter units simultaneously;
- the potential for reduced performance during cold weather events.

4.8 Process Start-up and Shutdown

The requirements for start-up and shutdown are covered in section 4.4 with respect to requirements for filter cleaning and ripening periods. It is imperative that slow sand cleaning is managed at sites to ensure that sufficient filtration capacity is available. Cleaning needs to be planned on a regular basis to minimise the risk that multiple units will require cleaning simultaneously as it can take several days to over 1 week to bring a filter back online.

Cleaning must be scheduled effectively to minimise the time that the filter bed is drained down. The more quickly a bed is cleaned and water is refilled, the shorter the time required for ripening and re-establishment of the *schmutzdecke*.

4.9 Process Troubleshooting

It is important to identify if the issues encountered are impacting a single slow sand filter, or if the entire filtration process is affected. Issues encountered with slow sand filtration will generally fall into one of the following categories:

- upstream water quality negatively impacting on filter operations owing to source water variability challenge or upstream process failure;
- filter performance (water quality and run time);
- filtration process.

A review of potential issues, areas of investigative action and potential corrective action have been provided for the above issues. These lists should not be considered exhaustive but should be used to develop local operational procedures.

4.9.1 Challenges due to upstream water quality issues

Upstream water quality issues will typically impact all filter units equally. Water quality parameters of interest include, but are not limited to, turbidity, colour, TOC, ultraviolet transmissivity (UVT), pH, temperature, alkalinity and chlorine demand. Recommended investigative and corrective actions are set out in Table 4.4.

Table 4.4: Malfunction: source water challenges and upstream process quality change

Issue	Recommended investigative action	Potential corrective action
Observed in all filters: negative change in water quality	Issue likely to be from upstream water quality including increased solids loading or the presence of algae	Optimise upstream process (if present) Increase cleaning frequency of slow sand filters Consider taking DWTP offline during periods of low water quality Consider provision of raw water storage to improve buffering capacity for raw water quality changes

4.9.2 Filter not achieving water quality targets

When a deterioration in the filtered water quality occurs, it is important to determine whether it is associated with all filters or just an individual filter. Tables 4.5 and 4.6 identify some common issues affecting filter performance and set out recommended investigative and corrective actions.

Table 4.5: Reduction in filter run time and/or filter water quality not achieving targets

Issue	Recommended investigative action	Potential corrective action
Filtered water turbidity exceeding feed water turbidity or exceeding target	Confirm there has been no flow fluctuations to the slow sand filter Confirm head loss profiles across filters Review raw/feed water quality, has there been a recent change? Inspect *schmutzdecke* layer to confirm it appears normal and healthy Check filter sand life Check a sample of filter sand for signs of penetration	Consider cleaning if only impacting one filter Address flow fluctuations *Schmutzdecke* layer may need re-establishment in reduced flow conditions A layer or all of filter sand may need removal and cleaning
Filter run time decrease (single filter)	Review hydraulic loading and flow profile Check for algal interference	Increase cleaning frequency Correct hydraulic loading
Filtrate colour exceeds water quality target	Check if deterioration of source colour or exhaustion of GAC layer if applicable.	Blend high-colour output with low-colour treated water if possible Consider replacing GAC layer

4.9.3 Filtration process deterioration

When a visible issue in the filtration process is observed during routine inspections, it is important to complete investigative and corrective actions as set out in Table 4.6.

Table 4.6: Filtration process deterioration

Issue	Recommended investigative action	Potential corrective action
Cracks in filter media surface or evidence that filter bed is breaking away from wall	Review flow information to confirm that there were no hydraulic disturbances Review level trends and confirm filter has remained adequately wetted (if a risk present) Check for algal interference	Skim filter sand to remove layer and allow filter to re-establish the *schmutzdecke* in low flow condition, while removed layer is cleaned and replaced later Correct any hydraulic disturbances Increase filter cleaning frequency
Visual evidence of deterioration of *schmutzdecke*	Review upstream water quality Review flow information. Determine whether flow disturbances occurred Check for algal interference Confirm that there is no issue (e.g. flow disturbances) that could be causing death or disturbance to the biological activity within the filter bed	Upstream corrective action as required Skim filter sand to remove layer and allow filter to re-establish deck in low flow condition, while removed layer is cleaned and replaced later

4.10 Advantages and Limitations of Slow Sand Filtration

Advantages of slow sand filtration are as follows:

- No chemical use required.
- No requirements for backwashing, meaning that limited process residuals are produced.
- No requirements for sludge disposal or treatment from routine operation. Whilst disposal of residuals containing bacteria and oocysts does arise from sand washing, there are no disposal concerns regarding chemical content.
- Minimal energy consumption compared to other media based filtration processes (e.g. RGF and pressure filtration).

Limitations are as follows:

- Less likely to reliably achieve a filtered water turbidity of < 0.2 NTU across all water quality and seasonal conditions.
- Requires a very large footprint compared with rapid gravity and pressure filters. This is due to the difference in loading rates between the two applications (0.3 m/h compared with 7–10 m/h).
- Cleaning of the filters is labour intensive and requires investment in specialist equipment to optimise mechanical cleaning/scraping.
- Disposal required of sand residual removed from filter bed during cleaning/scraping.
- Biological processes are impacted at low water temperatures with decreased efficiency below 6 °C.
- A high concentration of algae in source water can clog the filter bed rapidly and also cause taste and odour issues.
- A high suspended solids concentration in raw water can rapidly lead to clogging of the filter, resulting in significant reduction in filtered water output.
- The poor TOC removal capacity of slow sand filtration makes it not suitable for modern DWTP when TOC levels exceed 2.5 mg/l.

5. RAPID GRAVITY AND PRESSURE FILTRATION

5.1 Process Overview

RGF refers to gravity filtration systems in which the water level and/or pressure (head) above a granular media filtration bed forces the water to flow through the filter media. The filtration rate is significantly greater than that of slow sand filtration.

A pressure filter is similar; however, the filter media bed is completely enclosed in a pressure vessel. Water is forced to flow through the filter by a pressure gradient.

Rapid gravity and pressure filtration are in common use in Ireland and are part of most conventional water treatment plants.

The main filtration mechanisms (refer to Chapter 2) that apply are straining and adsorption.

The general process overview for both technologies is similar and is outlined as follows:

1. **Forward filtration**: water flows downwards through the filtration bed in a continuous process. As the filter run time increases, there will be an increase in head loss across the media bed due to clogging of the filter media, with particles removed from the feed water by the filtration process. This will eventually result in a decrease in filter performance and output. Clogging leads to turbidity (particulate) breakthrough, when solids are no longer being effectively retained within the filter bed.
2. **Backwash**: at regular intervals, the filter media bed must be backwashed to remove accumulated particulates. This should be done before there is any evidence of breakthrough in the bed. Continuous monitoring should be in place to automatically trigger a filter backwash if the head loss and/or filtered water turbidity exceeds the operational target. More commonly, water treatment plants will wash filters based on a pre-set number of hours in service before any issues with head loss and/or turbidity begin to materialise. The water used for backwash is usually filtered water produced within the plant before the addition of post-filtration chemical dosing. For modern water treatment plants there should be sufficient availability and/or storage of backwash water to allow for two filters to be washed in immediate succession.

   Generally, prior to backwashing, the media bed receives a high-rate air scour. Air is injected through nozzles in the filter floor, a piped header and lateral system or a newer, proprietary dual lateral underdrain system. This agitates and abrades the media granules, stripping much of the particulate matter attached to the media grains. There are two main backwash methodologies used at DWTPs within Ireland. They are described below:

   - **Sequential air–water wash**: a two-step backwash comprising (1) a vigorous air scour followed by (2) high-rate upwash with water to remove detached particulates to waste via an overflow weir or weirs.
   - **Combined air–water wash**: this comprises (1) a vigorous air scour for several minutes to dislodge particles from the bed, (2) a low-rate wash with a combination of air and water to further clean the bed by the formation and collapse of air bubbles and (3) a high-rate water-only wash to remove the dislodged particles.

Some installations may also include a cross-surface flush to assist in removing detached particles to waste. This is more common in older installations.

- **Fill, ripen and return to service**: the filter is refilled with water from upstream treatment processes. Initially, there will be a spike of elevated turbidity in the filtered water until the filter ripening period is complete. The term ripening originally related to this process in slow sand filtration but has become commonly used to describe the initial filtering period of a rapid gravity filter after backwashing. This involves the settled water passing through the bed, collecting particulate matter that has been dislodged from the filter media during backwashing that has remained in the filter matrix. Ripening is detailed further in section 5.4.3. To manage the turbidity spike, one of the following two strategies is employed:
  - **Run to waste**: the filter is run to waste during the ripening period, with all filtered water diverted to the water treatment residuals treatment train. A turbidity monitor on the filter outlet can determine when the filtrate is of acceptable quality to be directed back into supply. Many plants use a timer control to set a run to waste period after backwashing based on informed operational knowledge of the rinse time required to achieve the required turbidity target. It is considered best practice to run to waste a minimum of two bed volumes. Run to waste is the preferred methodology.
  - **Slow start**: Historically, a slow-start methodology was also used, in which the filter was returned to service immediately following a backwash at a low filtration rate (30% of the usual). The flow rate through the filter is slowly increased for a set time interval (typically 30–60 minutes) as required to minimise the turbidity spike observed during the ripening period. This allows any dislodged particulate matter remaining in the bed from the wash cycle to be removed into the filtrate gradually over the duration of the slows start, thus minimising turbidity spiking in the filtrate.

5.1.1 Filtration objectives

Rapid gravity and pressure filtration are typically used for the following filtration objectives:

- **Disinfection barrier**: as part of the disinfection barrier at a water treatment plant by providing the verifiable physical removal of targeted organisms including protozoa (*Cryptosporidium*, *Giardia*).
- **Turbidity reduction or reduction of particulates**: RGF is often the last turbidity removal process upstream of chemical and/or ultraviolet disinfection processes and must ensure that the turbidity targets for these processes are achieved.
- **Reduction of metals and/or TOC**: removal of solids can provide effective reduction of non-soluble metals and TOC. Upstream chemical conditioning, such as application of an oxidant or pH adjustment, can further enhance metals removal.

The EPA Advice Note on Turbidity in Drinking Water (EPA, 2009) recommends a filtered water turbidity target of < 0.2 NTU when filters are being used as a *Cryptosporidium* barrier. Turbidity performance criteria are set out in more detail in section 5.5.1.

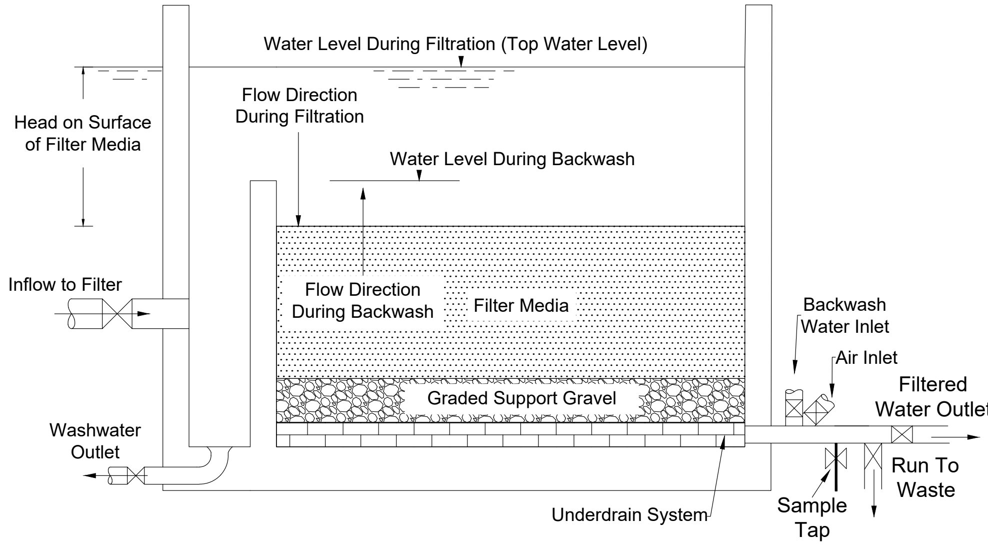
5.2 Process Equipment and Layout

5.2.1 Rapid gravity filters

A RGF system will typically have the following elements, as illustrated in Figure 5.1:

- **Filter shell**: the structure that holds the filter media bed and floor. In an open-topped filter this is typically of concrete construction; however, prefabricated stainless steel is also used.
- **Filter floor and underdrain**: the filter floor and underdrain structure has two main purposes: to provide evenly spaced collection of the filtered water from the bottom of the media bed and to provide an effective distribution system for air scour and backwash water flows. Filtered water is then collected in a combined filtered water channel. Details on a number of filter floor and underdrain design options available are provided below.
- **Filter weir with freeboard**: a weir is in place to allow for the collection and removal of backwash water. The backwash upwash water will exit the filter by flowing over the weir. There must be sufficient freeboard to allow for bed expansion to occur during the backwash without risking media loss. It is imperative that the weir is level. In some filter installations, troughs (also referred to as launders) suspended transversely above the filter surface are used to collect the waste backwash water for removal. This configuration is popular in North America and is gaining popularity in the United Kingdom. The use of troughs is considered to minimise the distance that particles must travel to be removed during the backwash and ensure a relatively even velocity of flow above the filter surface, thus reducing the risk of carryover of filter media while it is fluidised during backwash.
- **Media bed**: a media bed to a specified depth will be in place. Most DWTPs use a mono-media sand bed, or a dual-media bed with sand and anthracite. Often the filtration media is supported by gravel, which also prevents the air injection nozzles or apertures in the filter floor from being clogged by filter media particles. Installations with proprietary block floors may use media retention plates in lieu of a gravel support layer.
- **Backwash system**: filtered water, prior to the addition of any post-filtration chemical dosing, is the preferred source of backwash water. The minimum volume stored to serve the backwashing process should be sufficient to thoroughly wash at least one filter, preferably two or more. Following completion of backwashing, the storage tank providing water for backwashing will need to be refilled. This refilling should take place at a controlled, low rate to avoid hydraulic shock on downstream post-filtration chemical dosing processes. However, some facilities use final treated water with a small residual of free chlorine. Backwash pumps are normally provided to deliver the required upwards flow rates. Some installations may be able to provide the required upflow rates by using a backwash tank at a sufficient elevation above the filter surface in combination with a control valve. Air blowers provide the source of air for the backwash. The backwash flow rate should be verified to ensure adequate filter bed expansion is achieved during each backwash event.

Figure 5.1: Cross-section of a typical RGF filter.



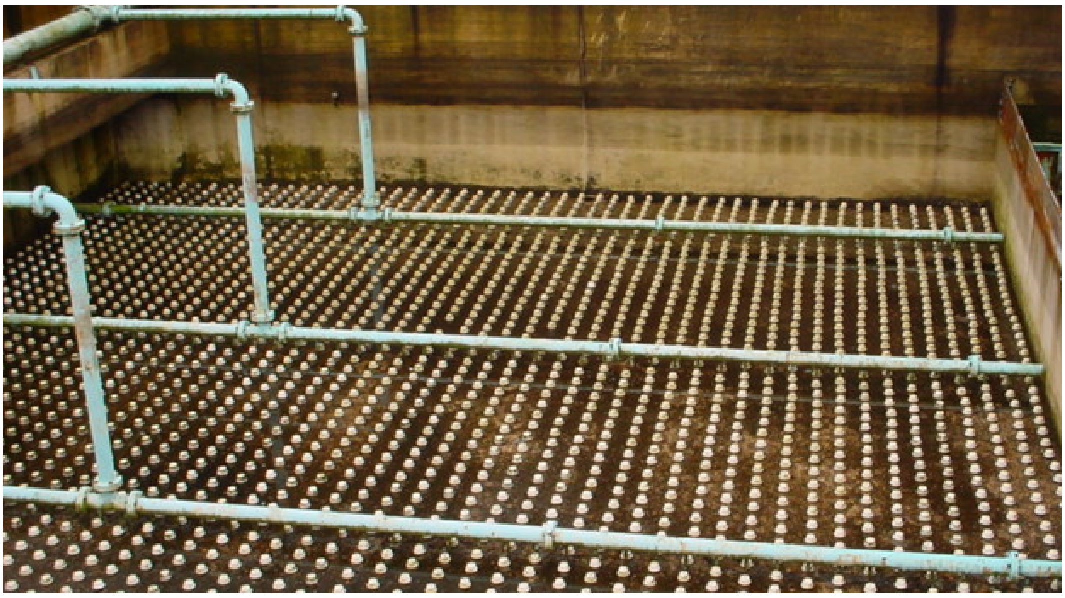
A number of different filter floor and underdrain design options are in common use. Historically a header and lateral system (Figure 5.2) was used to evenly distribute backwash water and air across the filter bed via laterals.

Figure 5.2: Example of a header and lateral floor.

(Photo courtesy of Xylem Inc.)

A monolithic (also called plenum) floor configuration has also been used (Figure 5.3), in which nozzles are set in a reinforced concrete floor set above a void space. This configuration offers improved distribution of air and water during backwash compared with header and laterals.

Figure 5.3: Example of plenum floor.



Newer installations often use proprietary modular block underdrain systems (Figure 5.4), which are engineered for efficient distribution of air and water across the filter media during the backwash sequence. The blocks are typically made of high-density plastic and are joined together to create a system that provides uniform distribution of air and wash water and even collection of filtrate. These systems are often accompanied by media retention plates and do not always require a gravel layer under the media bed.

Figure 5.4: Example of a proprietary block floor installation (Leopold® Block Floor System).

(Photo courtesy of Xylem Inc.)

It should be noted that the viscosity of water changes with water temperature. This means that at the same flow rate there will be much greater bed expansion during colder temperatures. This must be accounted for in any design to ensure both sufficient bed expansion during warmer temperatures and sufficient freeboard to avoid media washout during colder temperatures. Some DWTPs may provide a temperature compensation algorithm which will alter the backwash flow rates with changing water temperatures. This will require a variable speed drive (VSD) pump.

5.2.2 Pressure filters

Pressure filters are nearly identical to rapid gravity filters as outlined above. Some key differentiating elements of pressure filters are as follows and as illustrated in Figures 5.5 and 5.6:

- **Filter shell**: pressure filtration takes place within a prefabricated steel cylindrical pressure-rated vessel that contains the filter media bed, rather than in an open-topped structure. The size of the pressure filter vessel is generally restricted by what can be realistically transported to site, so they are generally < 4 m in diameter and 10 m in length (or height).
- **Configuration**: pressure filters vessels can be configured either horizontally or vertically. Horizontal filters are generally more economically advantageous for larger water treatment plants (> 4 million litres per day (MLD)). This is because, with a maximum media depth of 1–1.5 m, a greater number of vertical vessels is required to provide the equivalent filtration area to horizontal filters which can be several metres long.
- **Air-release valve**: installed at the highest point in the vessel to allow release of any trapped air.
- **Filter floor**: header and laterals are typically used for horizontal filters. Proprietary block floors are generally not used in pressure filtration applications.
- **Backwash configuration**: at some installations, it is possible to backwash a pressure filter without the use of backwash pumps, making use instead of the existing pressure. However, this arrangement should be treated with caution as the sudden reduction in flow from the filters when water is diverted from the treatment train as backwash water has the potential disrupt downstream processes.

Figure 5.5: Cross-section of a typical vertical pressure filter.

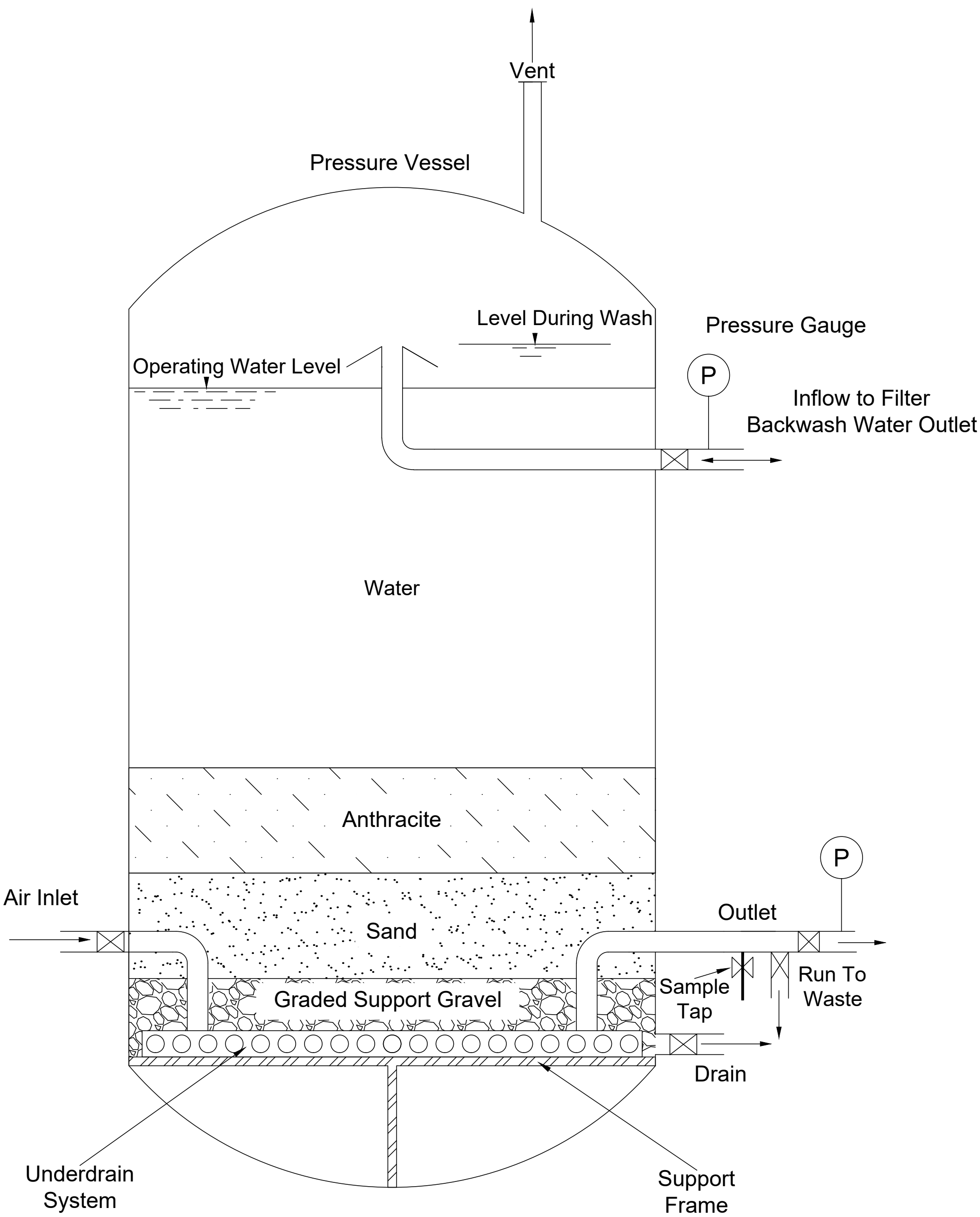
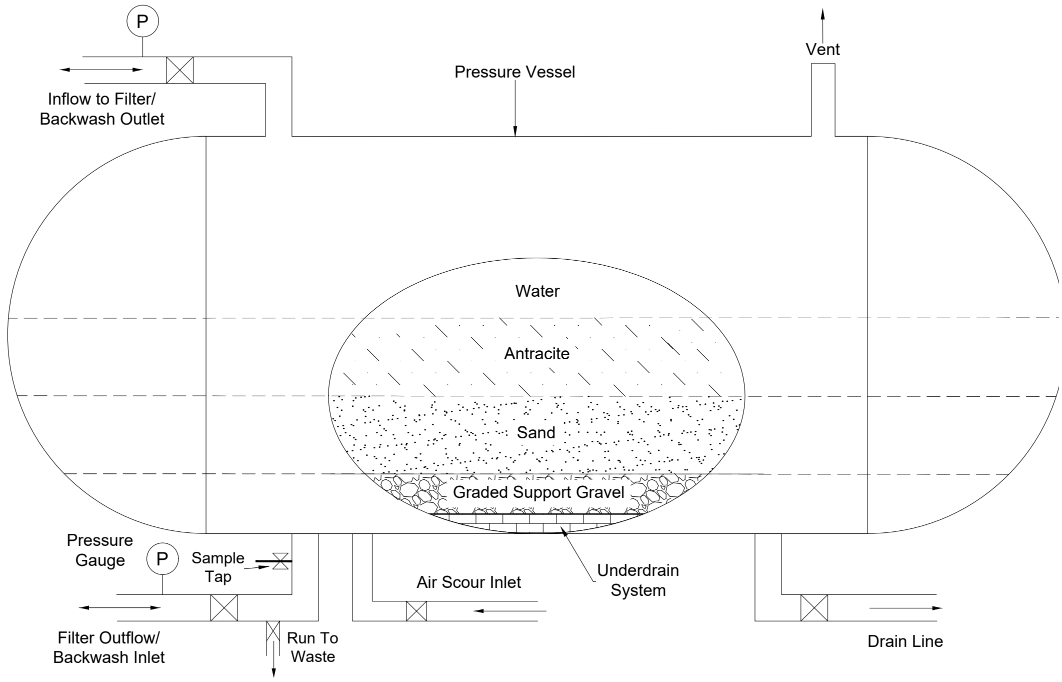


Figure 5.6: Cross-section of a typical horizontal pressure filter.



5.2.3 Considerations for filter media

The selection of filter media is a critical parameter in filter design.

A number of terms to describe the size and grading of filter media used in filtration have been developed over the years. These are defined as follows:

- d_{10}: the sieve aperture size through which 10% of the filter media (measured by weight) can pass. The d_{10} value is also called the effective size (ES).
- d_{60}: the sieve aperture size thorough which 60% of the media passes.
- d_{90}: the sieve aperture through which 90% of the media passes.
- Uniformity coefficient (UC): a measure of the grading of the material, determined by the ratio of d_{60}/d_{10}. A low UC indicates a tight grading, or smaller variation in particle sizes within the filter media.
- Porosity (P): the amount of void space in a filter bed, expressed as a fraction or percentage.
- Unstratified filter bed: a filter bed in which sand of different grain size is dispersed randomly throughout the bed.
- Stratified bed: a filter bed in which the sand is laid down in layers, with each layer consisting of sand particles within a similar size range.

Most recently installed rapid gravity filters and pressure filters in Ireland use a combination of sand and anthracite, often supported by a gravel support media. Although mono-media sand filters (Figure 5.7) are still used in existing DWTPs, most modern installations consist of around 500 mm of anthracite (ES 1.4 mm, UC = 1.5) and an additional 500–800 mm of sand with a UC of 1.4–1.5 and an ES of 0.4–0.6 mm (so-called dual-media filters as represented in Figure 5.8)).

Historically, some installations incorporated a third media layer of garnet. It was believed that the use of mixed media (also called tri-media or 'multi media') filters (Figure 5.9) could provide superior protozoa removal compared with dual-media filters. This layer was generally at least 150 mm in depth with media properties of ES 0.3 mm and UC 1.4. The denser garnet media would sit below the sand layer. The general current consensus is that this does not produce any discernible benefit in terms of increased filter runs or better filtrate turbidity to justify the additional cost of garnet compared with sand.

Anthracite is a much larger and lighter media. It will sit on top of the sand and is effective at filtering larger floc and particles that could cause the finer sand layer to clog more rapidly. Therefore, dual-media filters typically allow for a large volume of particulate retention because of the larger, less dense, anthracite layer, and allow for more efficient filtration through the finer sand granules. Anthracite used in Ireland typically has an ES of approximately 1.3 mm. Table 5.1 provides an overview of typical ranges for media characteristics.

Table 5.1: Filter media characteristics - typical ranges

Media	Effective size (mm)	Media density (g/ml)	Uniformity coefficient
Sand	0.5–0.7	2.6	1.3–1.7
Anthracite	1.2–1.4	1.5	1.3–1.7
Garnet	0.2–0.4	4.2	1.3–1.5

When iron and/or manganese removal is targeted, manganese dioxide or greensand media are often used. Activated carbon can be used to remove pesticides and eliminate unacceptable taste and odour. Alternative filtration media have been gaining popularity. There are numerous types, including engineered ceramic and glass media. A more detailed overview of alternative filter media is provided in section 10.2.

Minimum media bed depths for primary filters are usually determined by design specifications. One factor that is considered in determining the minimum depth of media required for primary filtration is a parameter known as the L/D ratio. This ratio reflects the bed depth (L) over the effective media size (D). The American Water Works Association has recommended that a minimum L/D ratio of 1200 is maintained to ensure adequate removal of *Cryptosporidium*.

For example: a bed of 1 m depth with 600 mm of sand, with a diameter (D) of 0.6 mm, and 400 mm of anthracite, with an ES of 1.3 mm, would have an L/D ratio as follows:

$$\frac{L}{D} = \left(\frac{600}{0.6}\right) + \left(\frac{400}{1.3}\right) = 1308$$

Additional factors that should be considered when selecting filter media are as follows:

- **Backwash system design**: the type and depth of media will have an impact on the rates of upflow that are needed to ensure full media bed stratification and achieve sufficient bed expansion to allow the media to be adequately cleaned during backwashing. The size and density of media also have a direct impact on the required upflow rates. Graded 16/30 sand (ES 0.54–0.7 mm), which is typically used in Ireland, requires a flow rate of approximately 35–40 m/h to achieve 15–20% bed expansion.

- **Filter media depth**: media losses are expected over time, with up to 2–3% expected per annum. Designers should ensure that a media depth marker plate is provided to clearly identify the media depth available and easily identify when a media top-up and/or replacement should be completed.
- **Filter run times and filtered turbidity performance**: finer media will have improved filter turbidities, but the beds will clog more rapidly and require more frequent backwashing.
- **Uniformity coefficient (UC)**: all media contain a gradient of particle sizes. After backwashing, finer granules within a media bed will restratify on the top of the media bed, and can reduce filter run times. Uniformity of media is therefore an important consideration. Design specifications for filters often define a UC. Media can wear over time, which can cause an increase in the number of smaller granules. Comparing the UC of older filter media beds can be an effective tool in determining media condition and deciding if a replacement is required.

Figure 5.7: Mono-media configuration.

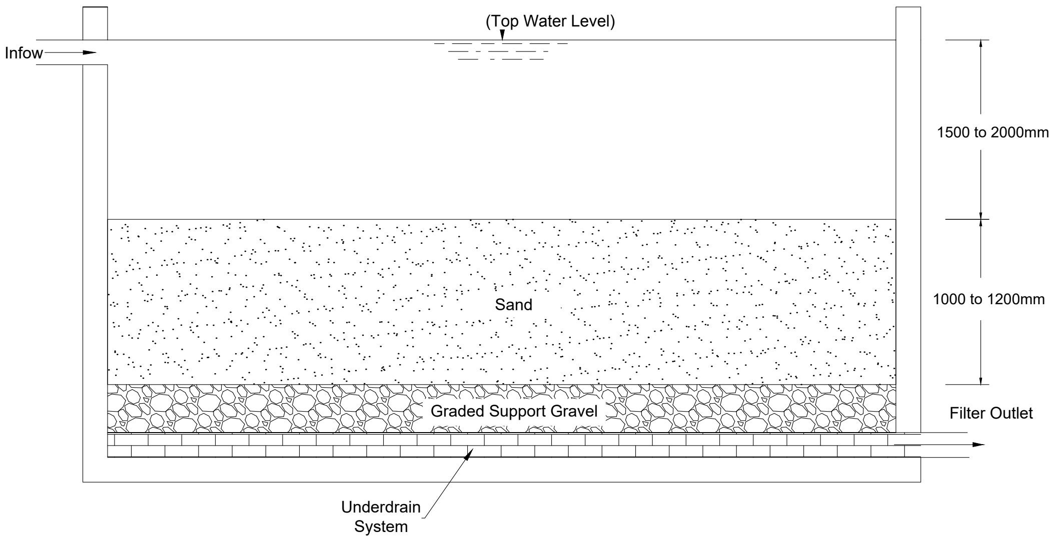


Figure 5.8: Dual-media configuration.

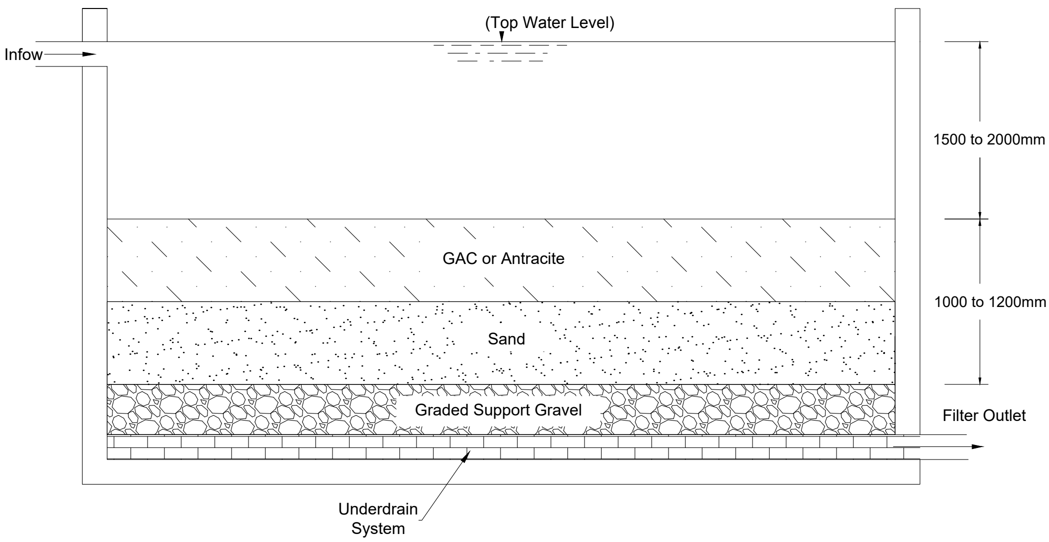
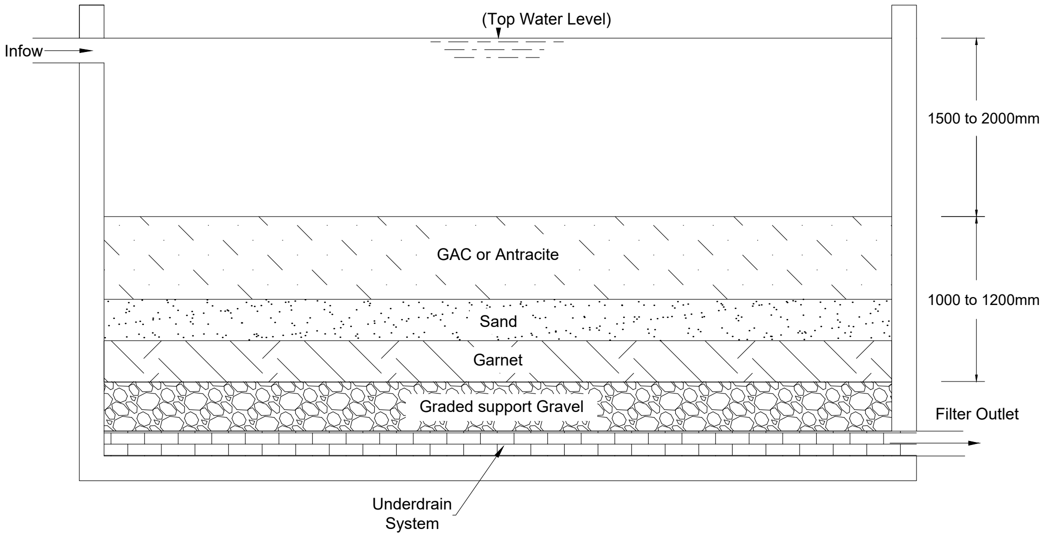


Figure 5.9: Mixed media, tri-media or multi-media configuration.



5.3 Design Considerations

The following design parameters are critical to consider for rapid gravity filters and pressure filters:

- **Type of filter**: the decision between pressure filtration and RGF is usually determined by a whole-life cost analysis. Typically, pressure filtration will be more cost advantageous at smaller sites (< 2 MLD). The main disadvantage of pressure filtration compared with RGF is that there is very limited capacity for visual checks and observations during backwashing to check that the filter is being backwashed properly.
- **Filtration rate (m/h)**: this is the rate at which water passes through the media bed, as determined by filtered flow (m^3/h) per surface area of the filter (m^2). The exact figure will be site specific, but generally rates in excess of 7.5 m/h for mono-media applications and 10 m/h for dual-media filters are considered inappropriate when protozoa removal is targeted. When only metal removal is targeted, higher loading rates of up to 15–20 m/h are generally considered acceptable.
- **Process redundancy**: the design must ensure that there is sufficient filter capacity (number of filters and available surface area of filtration media) that the maximum allowable filtration rate is not exceeded when filters are offline (i.e. for backwashing or required maintenance). Most larger plants will design on an *n* – 2 basis, meaning the maximum rate can be achieved with two filters out of supply, which allows for one in backwash and one out for maintenance. For small facilities with fewer than four filters, *n* – 1 is acceptable.
- **Backwash rates**: the backwash pumps and delivery system must be adequately sized to ensure that the target bed expansion is achieved. Most modern facilities target a minimum expansion of 20%. Older installations may have no or poor bed expansion. Consideration should be given to the changes in water viscosity with seasonal temperature variations. Colder water has a higher viscosity and will achieve greater bed expansions for a particular media and upwards flow rate than the same rate at a higher temperature. When multiple media types are used, the backwash rates must

also be sufficient to ensure that the filter bed is fully stratified, meaning there is a distinct boundary between media types. This does not apply to greensand (MnO_2) applications.

- **Air scour rates**: air scour must be provided to ensure sufficient agitation to the media bed to dislodge accumulated solids prior to their removal from backwash. Excessive air scour rates can lead to degradation of media, especially when anthracite is used.
- **Media bed depth**: this is the total depth of filtration media (which excludes the gravel support layer) that is provided. A minimum depth of 1 m is recommended by most regulatory jurisdictions. An L/D ratio of 1000–1500 is considered best practice. Retrofitting an increased media depth in existing filters to meet the minimum recommended depth is not always feasible but should be examined as part of any filter upgrading works.
- **Travel distance to weir** (gravity filters only): the horizontal travel distance of suspended particles during backwash should be minimised when possible. The recommended maximum travel distance is typically in the range of 1–5 m. If the travel distance is excessive, resettlement of solids agitated into suspension can occur, or excessive backwash water may be required to sufficiently remove suspended solids. Collection troughs (also called launders) are sometimes installed to shorten the required travel distance of washwater to be removed from the filter, as seen in Figure 5.10.

Figure 5.10: Example of used backwash water collection troughs.

(Photo courtesy of Xylem Inc.)

- **Basis of flow control**: two main types of control are typically used:
  1. **Constant level filtration** – inlet flow is divided equally between filters. This can be achieved by weirs on the filter inlets that are set up to ensure an even split. Each filter then operates at a constant water level, which can be ensured by controlling the filter outlet valve using a water level probe. Thus, the outlet valve will gradually open to compensate for the increased head loss resulting from particle removal during the filter run until the terminal head or the maximum run time is reached. The filter is then taken offline for backwashing. In this regime,

the filter output declines as filter clogging increases during the run period, leading to this method of control being known as declining rate filtration. This applies to RGF applications only.

2. **Constant rate filtration** – each filter is set up to pass an equal amount of the total flow arriving at the filter block. The flow through each filter is most commonly measured by a flow meter at each filter outlet. The flow meter modulates an outlet valve such that a constant rate is maintained through the filter, irrespective of its head loss due to clogging in service. When the filter reaches its terminal run time or head (head value at which it is taken out for washing – typically 1.5 m), the valve can shut automatically to take it offline. The system can also be set up to shut down all the filters in the event that the hydraulic loading onto the filters is too high.

The **constant level** (declining rate) has been used historically but is generally not used in modern installations.

5.4 Guidance on Operation

5.4.1 Forward filtration

The main objective of forward filtration is to maintain the filtered turbidity below the alarm threshold.

The following backwash triggers should be automated to initiate a backwash in order of priority:

- **turbidity**: when levels rise above a predefined operational trigger level;
- **head loss**: when levels rise above a predefined trigger level;
- **time**: operational set point based on current source water quality.

All three of the above should be implemented for all RGF and pressure filtration applications. A manually triggered backwash (i.e. by operator initiation) should always take precedence over any automated backwash queue.

Many water treatment plants will trigger the majority of backwashes based on time. This can be an effective way of managing multiple filters and reducing the impact on downstream processes (i.e. residuals treatment, supply of backwash water), or completing all backwashes during low-energy tariff periods. However, consideration should be given to avoiding hydraulic shock (i.e. increasing flow rate through in-service filters) and allowing effective treatment of process residuals.

When sufficient instrumentation and automation is available, triggering a backwash on head loss and/or turbidity will often allow for longer run times. In these instances, a maximum allowable filter run time should still be implemented.

Some seasonal variability is expected in filter run times. For example, a facility where algae can be a challenge can expect significantly reduced filter run times during summer blooms. Many plants in Ireland wash filters daily irrespective of the loss of head as a result of clogging or any increase in filtrate turbidity. This could be considered a conservative approach and results in increased operational costs due to comparatively greater use of filtered water, increased washwater to be treated and reduced effective life of pumping, air plant and filter media and associated pipework. However, it ensures that the filters are close to optimum in terms of particulate removal efficiency, providing sufficient capacity to cope with any large floc carryover from the previous treatment step.

5.4.2 Backwash

Removing a filter from supply for a backwash event should not have a negative impact on the remaining filters in service, which means that their loading rates and the rate of flow change must not exceed the recommended thresholds.

Prior to the commencement of the air scour phase, filters are drained to a pre-set level, typically 100–300 mm above the media bed. A RGF filter can be drained into supply; however, pressure filters should divert the "dump volume" to waste. This is because, when drain-down is commenced, the pressure in the vessel decreases sharply and particles from the media bed can become dislodged.

Regular inspection of the filter backwash is a critical aspect of process operation. While online instrumentation is effective at ensuring that filter water quality is maintained, manual checks on the filter backwash are critical to ensure the integrity of the filtration process.

As a minimum the following is recommended:

- **Visual inspection of air scour pattern confirming there is even** (Figure 5.11) **coverage.** No dead spots or areas of irregular agitation (Figure 5.12) should be visible, as these can indicate a blockage in the air distribution system such as a blocked nozzle (Figure 5.13). This visual inspection is not possible for pressure filters.

Figure 5.11: Example of a good backwash pattern.

(Photo courtesy of Xylem Inc.)

Figure 5.12: Example of poor backwash patterns. (A) dead area; (B) area of boiling and dead spot to the right; (C) scum pocket can indicate a dead area.

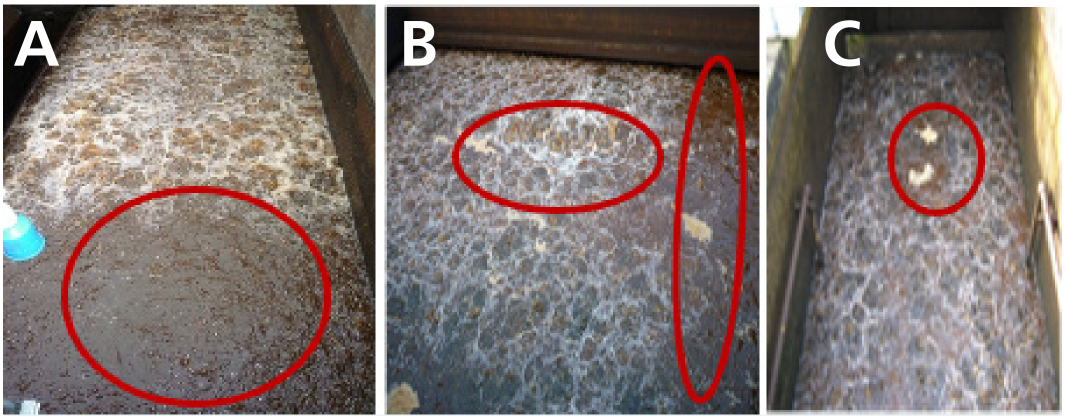


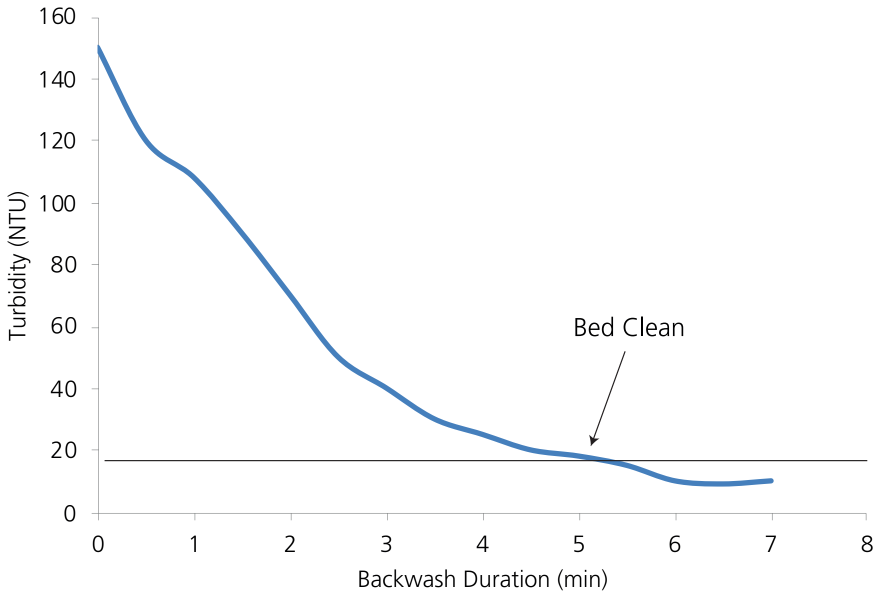
Figure 5.13: Example of blocked nozzle.

(Photo courtesy of Xylem Inc.)

- **Visual inspection of backwash confirming no media is being lost during backwash**: air release or excessive water flow rates between backwash sequence stages can often cause media to float to surface and be lost during the final upwash sequence step (not possible for pressure filters).
- **Complete turbidity removal profiles**: this is achieved by taking a sample of the backwash waste for the duration of the backwash (water only) at 1-minute intervals (rapid gravity filters and pressure filters).

An example of a backwash washwater turbidity profile is given in Figure 5.14. A filter bed is typically considered clean when the used backwash water turbidity is 10–20 NTU. The profile in Figure 5.14 is for a backwash that is 7 minutes in duration; however, the profile indicates that some optimisation is possible and the wash could be reduced to 6 minutes.

Figure 5.14: Example backwash removal profile.



In large plants consisting of many filters, consideration should be given to continuous turbidity monitoring of the backwash discharge to identify when it is sufficiently clean, to discontinue the final rinse and to ensure that the filter is ready for its next run. Although currently uncommon in Ireland, some water utilities in the United Kingdom have experimented with monitoring and profiling of suspended solids in a similar fashion to control backwash duration.

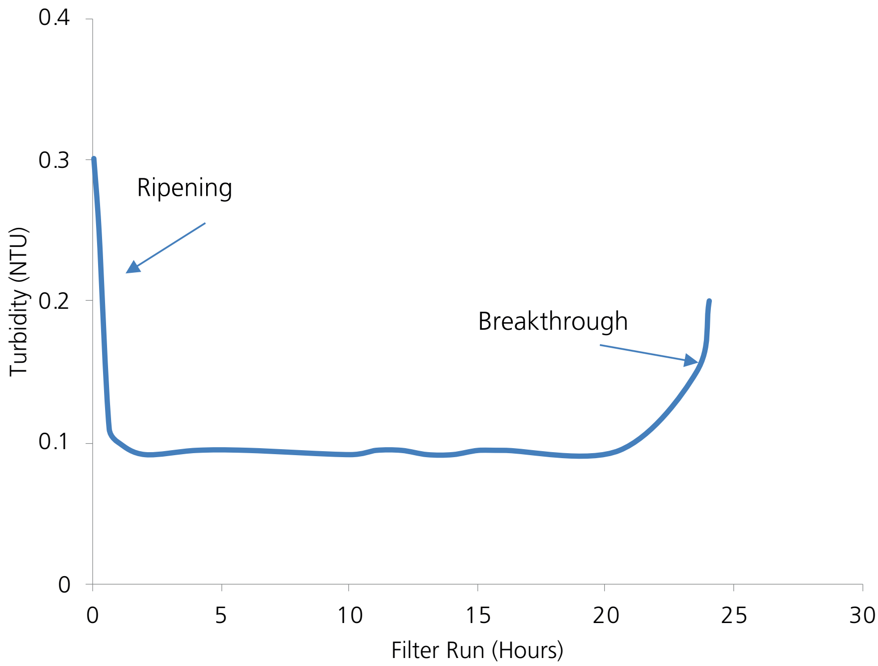
5.4.3 Filter ripening

Following the completion of a backwash cycle, backwash water remains below, within and above the media bed. As this used backwash water filters through the media when a filter is returned to forward filtration mode, a turbidity spike will be observed in the filtered water. In addition, there will be a temporary performance reduction as the media bed is reconditioned. Some accumulation of particulates within the media bed granules is required for optimal filtration performance. As fresh feed water is passed through the media bed, the turbidity spike will reduce until the filtered water turbidity target is achieved.

The filter ripening period can vary as a result of seasonal water quality challenges, the backwash regime or any upstream issues. It is considered best practice, where run to waste is available, to ensure that at least two bed volumes are discharged to waste from the filter before it is returned to service. The run to waste should be completed at the same filtration rate as when the filter will be returned to supply.

Where slow start is used, the turbidity profiles should be reviewed to ensure that the turbidity target is not breached. A typical filter turbidity profile identifying ripening and breakthrough is given in Figure 5.15. In this example the run to waste should continue until the filtered water operational turbidity target (for this particular DWTP) of 0.1 NTU is achieved.

Figure 5.15: Filter performance curve.



5.4.4 Process optimisation

The following parameters should be considered for process optimisation:

- **Coagulant residual (post-filter)**: achieving the site-specific turbidity target and maintaining a low residual coagulant post filtration indicates a well-optimised conventional water treatment process coagulation, flocculation and clarification (CFC) filtration. Although the parameter does not directly correlate to the filtration process, it can be useful to determine if any issues with the filtration process are due to the upstream CFC process.
- **Backwash duration**: the duration of the high-rate backwash can be optimised for varying water quality.
- **Filter run times**: similar to backwash duration, when source water and upstream water quality are good, the "time" setting for filter runs can often be extended, reducing backwash requirements.
- **Unit run volume (URV)**: this reflects the total volume of water filtered between backwash events. This can be a useful parameter to track filter performance, especially at DWTPs where there may be variations in daily flows through the treatment process. A reduction in the URV over time could indicate an issue with the media bed, backwash sequence and/or upstream water quality.
- **Normalised clean bed head loss (NCBH)**: this is calculated using a complex equation and allows comparison of the head loss profile for each run cycle of an individual filter. The head loss is recorded for each filter run cycle and normalised

for temperature and filter hydraulic loading. This allows for comparison of the head loss profile for each filter run cycle. The NCBH profile for a well-operated filter will return to approximately the same baseline value after each backwash. If this is not the case, there is likely to be an issue with the filter bed (e.g. clogging within the bed, inadequate backwash, source water quality issue). For a particular surface loading rate at a particular temperature, satisfactory backwashing is indicated by a constant clean bed head when the filter is returned to service. Normalisation (temperature correction) of the available data allows for direct comparison of filter runs across all seasonal temperature variations.

5.5 Critical Control Parameters

The identification of critical control parameters is an important aspect of applying the DWSP methodology. Table 5.2 summarises the recommended critical control parameters and associated control measure for rapid gravity filters and pressure filters that are used for primary filtration applications. This list should not be taken as exhaustive, but should be used as guidance as part of the DWSP development for a site.

Table 5.2: Critical control parameters for rapid gravity filters

Critical control parameter	Significance	Recommended control
Individual filtered turbidity	A backwash must be triggered when filtered water turbidity rises above the selected threshold. This indicates that the filter is exceeding its particle retention capacity. Filtered turbidity immediately after backwash is also important to ensure effectiveness of the run to waste and/or slow-start processes	Continuous online turbidity monitoring High-turbidity alarm and response procedure Process unit shutdown
Combined filtered turbidity	Identifies any issue having an impact on all filters. This is required to maintain for downstream disinfection (i.e. chlorine disinfection, UV disinfection)	Continuous online turbidity monitoring High-turbidity alarm and response procedure Treatment plant shutdown
Individual filter loading	Filtration rate cannot exceed the maximum allowable rate	Operational procedure for allowable throughput based on number of filters in service
Head loss	Head loss (or differential pressure) indicates when filter head loss has reached a critical value and the filter media bed has reached its capacity for effective turbidity removal	Online monitoring of head loss Head loss alarm and response procedure Process unit shutdown
Effectiveness of backwash	Effective backwash is required to ensure consistency and integrity of filter media bed	Operational check – visual backwash observations or online turbidity monitoring

Critical control parameter	Significance	Recommended control
Filter media bed depth	The filter media bed depth must be maintained	Operational check Routine measurement of media depths
Flow rate change: percentage flow increase per minute	An instantaneous increase in flow rate can cause hydraulic shock and dislodge particles from the filtration bed. Removing and/or returning a filter to supply or increasing or decreasing hydraulic flow rate through filter(s) must be completed at a controlled rate. Generally speaking, the increase should not be greater than 5% per minute	Operational procedure addressing increasing and decreasing flow rates through the DWTP
Level	Level in individual filters is used (depending on control methodology used) to confirm equal flow split between filters	Continuous online level monitor
Filtered water-soluble metals residual (mg/l)	Measuring soluble metal residuals to assess an increase in residual coagulant is an effective tool to identify an issue with filtration and/or upstream CFC	Daily (on-site test) or continuous online monitoring

5.5.1 Turbidity performance criteria

For rapid gravity filters and pressure filters that provide a barrier for *Cryptosporidium*, or provide the final turbidity barrier upstream of disinfection processes, the minimum turbidity performance criteria are defined in Table 5.3. The limits apply to both individual filters and to all filters combined.

As outlined in Chapter 3, facilities should be designed and operated to achieve performance criteria according to one of the following:

- the log credit approach;
- the turbidity performance approach.

Table 5.3: Turbidity performance criteria for RGF and pressure filtration

Type of event	Applies	Limit	Definition of event	Response
Regulatory event	All DWTPs	1 NTU	3 or more consecutive readings	Immediate response and/or shutdown followed by appropriate investigation and intervention

Type of event	Applies	Limit	Definition of event	Response
Upper operational event	DWTPs using log credit approach	0.5 NTU	3 or more consecutive readings	Immediate corrective action to be taken or process unit shutdown considered
Operational event	DWTPs using log credit approach	0.3 NTU	15 or more consecutive readings	Appropriate operational intervention and investigation Corrective action to be taken or process unit shutdown considered
	DWTPs using turbidity approach	0.2 NTU	15 or more consecutive readings	

5.5.2 Guidance on log removal credits

Rapid gravity filters and pressure filters can achieve a 3 log removal credit for protozoa at conventional filtration DWTPs, and 2.5 log credits for protozoa at direct filtration DWTPs. No log credit can be granted if a coagulant is not dosed continually upstream of the filter.

At facilities where the log credit approach is being applied the following must be achieved as a minimum:

- All water passes through full coagulant, flocculation (if provided), clarification (if provided) and filtration.
- Continuous monitoring of turbidity is provided for each individual filter and all filters combined.
- Turbidity does not exceed 0.3 NTU from any individual filter for more than 15 consecutive readings or 0.5 NTU from any individual filter for more than three consecutive readings without operational intervention and corrective action.
- Turbidity does not exceed 1.0 NTU for more than three consecutive readings from any individual filter.

When filters deliver consistently good performance, additional log removal credit for enhanced filtration can be considered, as follows:

- 0.5 log when the overall combined filtered turbidity does not exceed 0.15 NTU for more than 15 consecutive readings;
- 1 log when turbidity for each individual filter does not exceed 0.1 NTU for more than 15 consecutive readings.

5.5.3 Regular operational checks

Table 5.4 outlines recommended operational checks to be completed regularly for rapid gravity sand filters and pressure filters.

Table 5.4: Recommended operational tasks for RGF processes

Task	Description	Recommended frequency
Optimisation of high-rate backwash duration	Collect samples for every 1 minute of the high-rate backwash and measure turbidity. The bed is considered clean when turbidity is less than 10–20 NTU. Consider adjusting the backwash time. Seasonal variations are expected	Weekly or as required by variability in source water
Visual inspection of media (RGF only)	Inspect surface of media to ensure that it is free of biological growth, there are no visible cracks and the filter bed is flat and not separating from the walls	Every visit
Visual observation of backwash (RGF only)	Complete full visual inspection of backwash from drain-down to run to waste	Every filter once per 10 backwash cycles
Media depth check	The depth of media should be measured, or a datum point should be available in the filter to confirm that minimum bed depth is maintained	Quarterly
Media coring	A sample of media should be taken from the media bed to inspect for poor media conditions and confirm that the media bed is fully stratified and clean after backwash	Twice per annum
Backwash expansion	The backwash expansion should be measured twice annually to capture the warmest water temperature (minimum expansion) and coldest temperature (maximum expansion). An example of a backwash expansion measurement tool is shown in Fig. 5.16 The exercises should be repeated on multiple filters, and performed for each backwash pump, when a duty standby arrangement is in place	Twice per annum
Clean filter walls and launders	The filter should be kept clean of any biological growth including algae/carryover deposits from floc and other biological growths	As required
Filter outlet valves	Filter outlet valves should be tested to confirm that they are fully functional and do not allow water to pass forward when in the shut position	Annually
Filter media integrity	Samples removed from the filter bed should be sent for sieve analysis to confirm the UC	As required (> 5 years of age)

Figure 5.16: Backwash expansion measurement tool is shown

5.5.4 Operational records

In addition to the monitoring data available from online instrumentation, it is important to ensure that all operational logs are completed accurately and, as a minimum, the following information is captured:

- the date and conclusion of all backwash observations, bed expansions, media coring;
- the backwash set points and any adjustments made;
- the date and conclusion of any backwash washwater profile sampling;
- the size and key characteristic of media in each filter (e.g. UC, d_{10}, d_{60}, age of installation and any condition or sieving tests completed);
- recorded media depths, including assessment of estimated percentage loss;
- raw water and filtered and final water quality (online instrumentation and on-site testing records) including water temperature;
- details of any incidents, unusual events or notable observations with respect to raw water quality (i.e. algal blooms, storms, etc.);
- details of any floc carryover events.

5.5.5 Guidance for media checks

Media samples can be sent for sieve analysis to determine the UC to compare to that of the original virgin (unused) media. If the UC has increased, this can indicate that there are increased "fines" present and that some degradation of media has occurred.

Anthracite, being a relatively light material, is more vulnerable to degradation. Air scour is believed to contribute to a reduction in the angularity of anthracite over time. Sand can become worn over time but will probably have a longer effective life than anthracite. Where dual-media filters are installed, plant operators can expect to top up the anthracite layer on a more frequent basis than the sand bed.

A lifespan for filter media cannot be specified as the expected media life will depend on many factors, including backwash sequence and frequency. It is recommended that, over 5 years, the media be tested every 1–2 years to confirm that no significant degradation has occurred. Sand can be expected to last at least 15–20 years.

5.5.6 Performance assessment of filters

A general performance assessment should be completed regularly for the filtration process. Elements to be considered include the following:

- Review all operational data (i.e. turbidity, head loss).
- Review triggers for backwash initiation.
- Inspect and confirm operation of all valves and piping servicing each filter. Ensure that valve seals are closing as intended.
- Review filter media and confirm ES and uniformity.
- Review backwash system and air scour patterns.
- Confirm filter media depth.
- Confirm that all filters are performing equally (e.g. run times, filtered turbidities).
- Review impact of raw water and/or feed water quality variability on filter performance.
- Review hydraulic control, and confirm that flow distribution and flow changes are effectively managed with no impact to filtered water quality (e.g. impact to in-service filter when one from the block is removed from backwash, filter performance when flow throughput through the DWTP is adjusted).

5.6 Upstream and Downstream Considerations

5.6.1 Process inputs

The following inputs are required to support RGF and pressure filtration:

- **Backwash water**: water for backwash is often sourced post filtration, most commonly before any downstream chemical (i.e. chlorine) addition. However, some treatment plants will use final treated water as the backwash water source. The presence of chlorine is not harmful to media; however, consideration must be given to the disposal of chlorinated wastes from the water treatment plant. This is typically not an issue given the generally high chlorine demand of backwash wastes.

5.6.2 Process residuals

The following process residuals are produced by the filtration process:

- **Dump volume** (pressure filters only): after removing a pressure filter from the supply, the volume drained from the pressure vessel must be directed to waste.
- **Used backwash water**: the volume produced is usually equivalent to approximately two to three bed volumes. Backwash water should be allowed to settle to facilitate the thickening of solids. It is important to ensure that there is sufficient capacity to allow for all filters to be backwashed under worst-case operating conditions (typically assumed to be a 12 to 24-hour filter run time) without being constrained by insufficient capacity for settlement of the waste washwater.
- **Run to waste**: when the filter is run to waste, the waste water is either disposed of (sewer or to natural environment) or returned to the head of the DWTP. In these cases, a minimum quality (usually turbidity and metals residuals) is recommended. The water should be returned upstream of any coagulant dosing. Any process residuals that are disposed of to the natural environment must meet any regulatory requirements associated with these discharges with no deleterious impact on the receiving water body.

5.6.3 Upstream considerations

Filtered water quality is highly dependent on the satisfactory performance and subsequent water quality from upstream processes, namely coagulation and clarification. A decrease in filtered water quality is generally more likely to indicate an issue with upstream processes than with the filters themselves. Possible issues that could occur are as follows:

- Floc carryover from clarification can contribute to shortened filter run times.
- Poor coagulation can cause fine floc to bypass the clarification process, leading to decreased filter run times and a reduction in water quality (i.e. coagulant metals residuals, turbidity, UVT).
- Poor control of inlet or outlet hydraulics in upstream clarification stage can cause uneven performance and higher than expected turbidity in the feed water to the filters.
- Excessive polymer dose can cause filter media to become sticky and congealed and can have an impact on the effectiveness of the backwash sequence.
- Upstream flow disturbances or ineffective or insufficient desludging of clarification process can lead to increased solids carryover to the filtration process.
- A sudden bloom of algae into the water treatment plant can cause pH issues and have an impact on coagulation. The presence of algae can blind the filter bed, resulting in decreased filter run times.

5.6.4 Downstream considerations

Backwash water must be sourced from downstream of the filters. Diverting water for backwash requirements can have an impact on flow (and flow measurement). This can have a negative impact on downstream processes, especially chemical dosing control at plants where chlorine is dosed immediately after the filters.

Backwash wastewater and wastes from the dump volume and run to waste require further treatment prior to either recycling to the head of the DWTP or discharge to sewer or local watercourse. Poor management of backwash cycles at the DWTP can put strain on these processes.

5.7 Process Start-up and Shutdown

It is the nature of the rapid gravity filters and pressure filters that frequent removal from supply is required to complete backwashing. However, the following is recommended for long-term shutdowns:

- To be considered on start-up of an offline filter:
  - A filter that has been left offline for more than 48 hours should be backwashed before being allowed to re-enter the supply (if possible).
  - It may be advantageous (especially with uncovered outdoor filters) to soak the filter in chlorine overnight if a filter has been offline for longer than 72 hours. This will help inactivate any accumulated biological activity while the filter was offline. If this is undertaken, care must be given to the process residuals system at the plant, as not all systems are designed for chlorinated backwash wastes.
- To be considered on shutdown:
  - If a filter is to be removed from supply for an extended period of time, it is recommended that the filter be backwashed before it is taken offline. This will reduce the risk of mud-ball formation within the filter bed and reduce biological activity while the filter is not in use.

5.8 Process Troubleshooting

It is important to identify if the issues encountered are impacting a single filter, or if the entire filtration process is affected. Issues encountered with RGF and pressure filtration processes will generally fall into one of the following categories:

- a negative impact of upstream water quality on filter operations as a result of source water variability or upstream process failure;
- filter performance (water quality and run time);
- issues with filter process (backwash effectiveness and/or media bed).

Areas of investigative action and potential corrective action for the above potential issues are reviewed below. These lists should not be considered exhaustive but should be used to develop local operational procedures.

5.8.1 Challenges due to upstream water quality issues

Upstream water quality issues will typically be identified as they have an impact on all filter units equally. Water quality parameters of interest include, but are not limited to, turbidity, colour, TOC, UVT%, pH, temperature, alkalinity and chlorine demand. Table 5.5 identifies some common upstream water quality issues and the associated recommended investigative and corrective actions.

Table 5.5: Malfunction: source water challenges and upstream process quality change

Issue	Recommended investigative action	Potential corrective action
Observed in all filters: negative change in water quality increase coagulant metal residuals high head loss reduced filter run times	Issue likely to arise upstream Review coagulation including inspection of floc size, clarified turbidities, pH, turbidities, etc. Review coagulant dose	Adjust coagulant dose Adjust pH/alkalinity control Adjust clarification desludging removal frequency Consider adjusting set point for filter run times Consider flow reduction to reduce filter loading rate
Increased filtered run times with reduction in water quality (final, filtered and/or settled)	Review coagulant dosing. Is there evidence of poor floc formation which can pass through filters?	Adjust coagulant dose Adjust alkalinity and/or coagulant pH

5.8.2 Filter not achieving targets for run time and/or water quality

It is important to determine if the filtered water quality deterioration is having an impact on all filters. Table 5.6 sets out some common issues that can be observed in this regard and the associated recommended investigative and corrective actions.

Table 5.6: Reduction in filter run time and/or filter water quality not achieving targets

Issue	Recommended investigative action	Potential corrective action
Filtered water quality decrease and/or filter run time decrease (all filters)	Verify upstream coagulation and clarification performance Review backwash duration	Adjust backwash duration to improve solids removal Consider flow reduction to reduce filter loading rate As per Table 5.5 for source water and upstream challenges

Issue	Recommended investigative action	Potential corrective action
Filtered water quality decrease (single filter)	Confirm equal flow split between filters Confirm no excessive flow changes to filter due to backwash or uneven flow split Confirm outlet valve performance Inspect media bed Complete inspection of backwash	Repair to filter outlet valve Inspection of underdrain and nozzles if dead spot(s) identified Corrective works as required by investigative actions
Filtered run time decrease (single filter)	Visual observation of backwash Confirm even air scour and backwash pattern Confirm media bed depths Confirm turbidity removal profile during backwash Confirm equal flow split between filters	Inspection of underdrain and nozzles if dead spot(s) identified Corrective works as required by investigative actions
Filtered turbidity spikes are observed	Review run to waste/ slow start to confirm it is adequate Confirm satisfactory flow to and operation of online instrumentation Verify that no rapid flow changes have occurred at the DWTP Determine if spikes correspond to another operational activity (i.e. washwater returns, valve operation, etc.)	Consider adjusting run to waste and/or slow start methodology Corrective works as required by investigative actions

5.8.3 Filtration process deterioration

Regular visual inspections of the filter backwash (with acknowledgement that there is limited capacity to assess pressure filters) and the condition of the filter media bed are imperative to identify any issues that require corrective action. When an issue is observed, it is important to complete investigative and corrective actions as set out in Table 5.7.

Table 5.7: Filtration process deterioration

Issue	Recommended investigative action	Potential corrective action
Cracks in media surface Mud-balls present Congealing of media in filter bed	Review backwash performance including turbidity removal profiles. Is the wash duration effectively cleaning the bed? Visually observe backwash. Confirm correct sequence Confirm adequate air scour and backwash rates Confirm adequate bed expansion Investigation into media condition Review coagulation, clarification performance. Confirm polymer dose rates	Attempt backwash with increased washwater duration Reduce polymer dosing rates As per above Table 5.5 for source water and upstream challenges Further inspection of media bed required to inform corrective action (i.e. bed cleaning, media top-up, media replacement)
Media boils during backwash Excessive media loss or visible disturbance in media bed	Visual inspection of backwash Confirm even air scour pattern to identify a potential blockage Confirm no air entrainment contributing to media loss	Confirm source of media boils Corrective action likely to include cleaning of underdrain system, nozzle cleaning and/or replacement

5.9 Advantages and Limitations

Advantages of rapid gravity and pressure filtration are as follows:

- RGF and pressure filtration are proven and common processes used in drinking water quality.
- There are clear performance requirements with respect to turbidity targets that give plant operations teams confidence that the process is providing effective treatment.
- Lesser site footprint than the traditional slow sand filtration.
- Treatment integrity can be maintained with continuous online instrumentation. Filters that start to produce poor-quality water can be instantly removed from supply.

Limitations are as follows:

- Visual observations of backwash are not possible with pressure filtration, making early identification of any potential issues more challenging.
- Up to 5% of the filter throughput can be lost as a result of backwashing requirements.
- Backwashing is a time-consuming process, with the full cycle often taking 45–60 minutes to complete.

5.10 Guidance for Specific Applications Involving Rapid Gravity Filters and Pressure Filters

5.10.1 Iron and manganese removal

Iron (Fe) and manganese (Mn) are present in both particulate and soluble forms. When the metals are present in soluble form, treatment involves applying an oxidant to change the metal state from a soluble to a precipitate form. Particulate forms of the two metals can then be removed using filtration. When iron and manganese removal is targeted in a media filter, it is completed in either RGF or pressure filters.

There is a consumption of alkalinity associated with the oxidation of manganese and iron. Lack of natural alkalinity to facilitate the reduction has not been seen to date but should always be checked.

When pre-chlorination is used to oxidise metals, leaving a free chlorine residual in the filtered water, sodium bisulphite can be used to quench any chlorine residual coming off the filter so as to minimise the potential for chlorine-based disinfection by-products downstream.

Daily backwashing is recommended to maintain the effectiveness of a manganese dioxide filter.

5.10.1.1 Design considerations

In addition to the design considerations outlined in section 5.3, the following parameters may be considered:

- **Selection of oxidant**: oxidants used are air, or a strong chemical oxidant including chlorine, potassium permanganate, chlorine dioxide or ozone. Oxidation effectiveness is influenced by pH and water temperature, as seen in Table 5.8.

Table 5.8: Guidance for oxidation of iron and manganese (Twort, 2016[1]).

Target metal	Oxidant	Stoichiometric quantity of oxidant (mg/mg Fe or Mn)	Reduction in alkalinity (mg CaCO3/mg Fe or Mn)	Optimum pH
Fe(II)	Oxygen	0.14	1.8	> 7.5
Mn(II)	Oxygen	0.29	1.8	> 10.0 > 7.5–8.5[a]
Fe(II)	Chlorine	0.63	2.7	> 7.0
Mn(II)	Chlorine	1.29	3.64	> 9.0 > 7.5–8.5[a]
Fe(II)	Potassium permanganate	0.94	1.49	> 7.0[b]
Mn(II)	Potassium permanganate	1.92	1.21	> 7.0[b]
Fe(II)	Chlorine dioxide	0.24	1.96	> 7.0

1 Reproduced from Twort (2016), Table 10.2, p. 423.

Target metal	Oxidant	Stoichiometric quantity of oxidant (mg/mg Fe or Mn)	Reduction in alkalinity (mg CaCO3/mg Fe or Mn)	Optimum pH
Mn(II)	Chlorine dioxide	2.45[c] 0.49[c]	3.64 2.18	> 7.0 > 7.5
Fe(II)	Ozone	0.43	1.8	Acidic preferred
Mn(II)	Ozone	0.81	1.8	Acidic preferred

[a]With use of catalytic media.

[b]Reaction can proceed at pH > 5.5.

[c]Variation based on reference source used as outlined in Twort (2016).

- **Filtration media**: the presence of catalytic media such as greensand will lower the pH required. Manganese removal filters using sand and chlorine typically require an optimal pH of 9. The use of catalytic media will lower the pH required to the range of 7.5–8.5 manganese dioxide (MnO_2). The media used in manganese removal applications, such as MnO_2 or greensand, will remove soluble manganese by adsorption. The media are often used in combination with other media (about 10–20% by volume) and will intermix with other media. However, where the filters are installed with the sole goal of metal removals, 100% of the filter bed can contain the specialised media. In addition to MnO_2 media, there are some proprietary media on the market to which many apply a MnO_2 coating. The design must take into account media properties when calculating the backwash rates required to ensure adequate bed expansion.
- The achieved reduction in iron and manganese will be application specific and is dependent on a number of factors, including pH (> 7.5 considered optimal for removal), alkalinity, influent loadings on the filter feed water, the speciation of the metals (soluble or precipitate forms) and the application of an oxidant. Some applications may not require the use of oxidant, but it should be considered essential when feed water manganese exceeds 250 µg/l.
- **Media regeneration**: where catalytic media are used, the media must be regenerated. This can be done by continuous regeneration by constant application of an oxidation ($KMnO_4$ or chlorine typically). Intermittent regeneration by potassium permanganate can also be completed. In Ireland, using greensand in combination with chlorine is the most common process selected.
- **pH adjustment**: the pH of the filtration stage must be in the sufficient range to ensure the removal of iron and/or manganese. At sites where metal removal is targeted in a second stage of filtration, alkali dose is often added to maximise the removal. Care must be taken at those sites where an aluminium-based coagulant is used. Aluminium is soluble at a high pH, and therefore all aluminium floc must be removed upstream (in first stage filtration) or it will dissolve.

- **Selection of oxidation process**: the oxidation of iron with air is slow and is very pH dependent. For example, an estimated 40 minutes is required at pH 6.9, whereas 10 minutes may be sufficient at pH 7.2. The reaction for manganese is much slower and requires a higher pH and is therefore not considered viable. For this reason, chemical oxidation is usually used when manganese removal is targeted.

Biological filtration is also an option for manganese control. This is not in common use in Ireland, currently. A basic overview of biological filtration is provided in Chapter 10.

5.10.1.2 Critical control parameters

In addition to the critical control parameters outlined in section 5.5, the parameters in Table 5.9 should be considered.

Table 5.9: Critical control parameters for iron/manganese removal process by filtration

Critical control parameter	Significance	Recommended control
Chlorine residual (or oxidant residual)	Applies to secondary filtration applications when chlorine is used to target metals removal. Ensure satisfactory dose to drive the reaction to completion	Continuous online instrumentation
pH	Applies to filtration applications when pH is adjusted upstream for metal precipitation and removal in the media bed	Continuous online instrumentation
Metals residuals (total and soluble)	Sampling and/or monitoring for both the total and soluble forms of target metals will verify that the metals removal process is operating successfully	Online instrument and/or sampling

5.10.1.3 Operational guidance

The following operational guidance is provided:

- When iron and manganese removal is targeted, new (virgin) media often require "seeding" time to build up a coating on the media surface to reach maximum removal capacity. When media replacement is required, it is recommended to stagger this to minimise the impact on final water quality.
- In the event of process issues, consideration should be given to downstream processes. Iron and manganese can lead to fouling on UV disinfection lamps. Manganese and iron can precipitate out in chlorine contact and reservoir storage tanks and settle. These settled sediments, if agitated, can cause discoloration of water in the distribution network.

5.10.1.4 Advantages and limitations

Advantages are as follows:

- robust technology;
- multiple objectives accomplished in a single process unit.

Limitations are as follows:

- Overdosing of potassium permanganate over what is required for oxidation can lead to a pink colour in the final water.

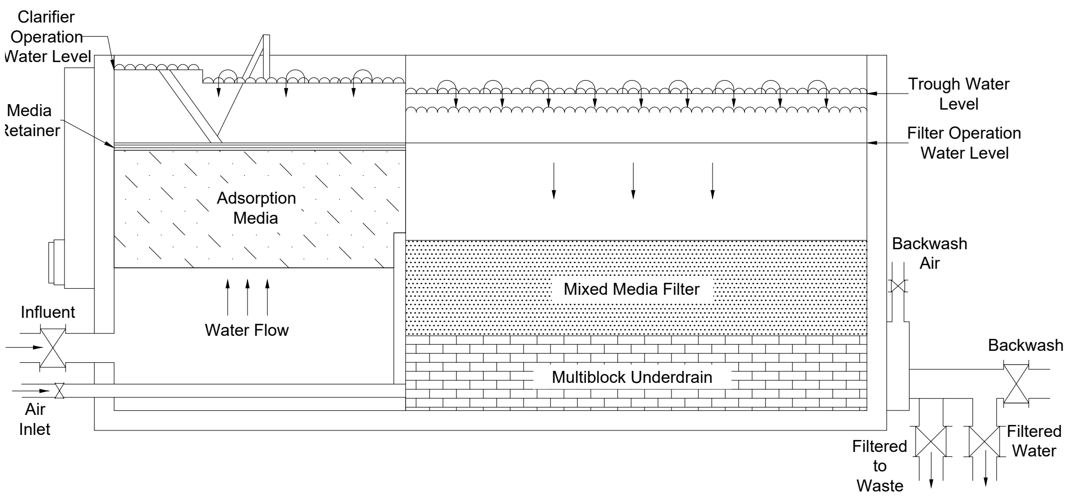
- Any excess chlorine not used up in the oxidation process can cause DBP formation in the final water unless this is removed by sodium bisulphite.
- Both manganese and iron removal are pH dependent.
- Control and monitoring of feed water quality, pH, and oxidant dose rate and final water quality can be critical when the concentration of the metals to be removed can vary.

5.10.2 Combined clarification filtration units

Two typical packaged units that contain both clarification and filtration within a single-stage process unit are currently used in Ireland.

Adsorption clarifier: coagulant is added as water enters the bottom of the unit which contains a bed of plastic media in an upflow clarifier as illustrated in Figure 5.17. Floc will adsorb to the media. The units then typically have an integrated downwards flow media filter in a second chamber. The systems (both the clarifier media and filter) are periodically backwashed by fluidising the bed and applying further agitation by air.

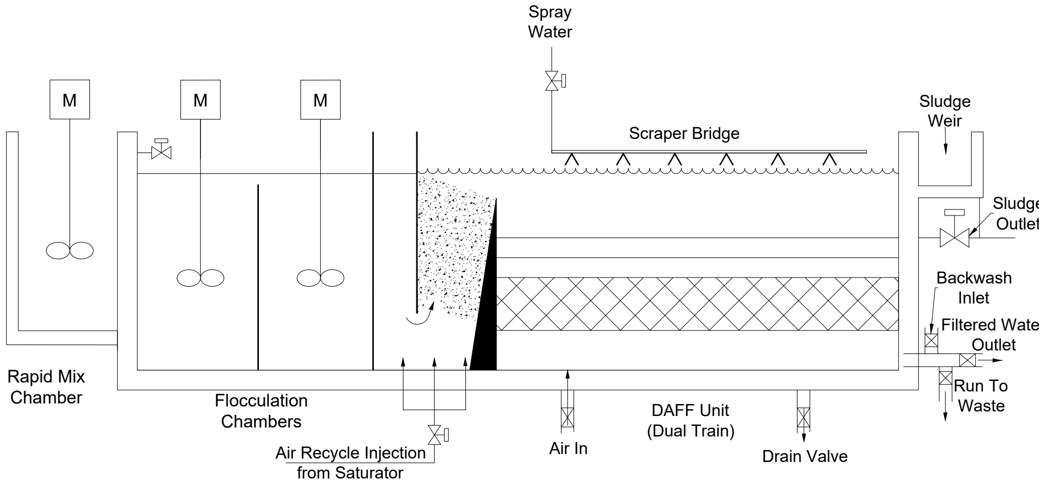
Figure 5.17: Cross-section of adsorption clarifier.[2]



Dissolved air flotation with filtration (DAFF): **this** involves combining clarification by dissolved air flotation and filtration in a single process unit. The basic structure is shown in Figure 5.18.

2 Accessed online 25 October 2018. http://awcwater.ca/product/ac-clarifier/

Figure 5.18: Cross-section of dissolved air flotation with filtration unit.



5.10.2.1 General design considerations

The combined clarification–filtration package plants are typically purchased directly from the manufacturer or designed directly for a particular site. The core requirements outlined for RGF earlier in this chapter apply.

5.10.2.2 Critical control parameters

The critical control parameters presented in Section 5.5, Table 5.2 and table 5.9 still apply.

5.10.2.3 Operational guidance

The main challenge with combined clarification–filtration package plants is the inability to complete continuous online monitoring of the clarification stage. Operational response procedures and filtration instrument alarm settings should take this into account.

Operators may consider more frequent review of the backwash washwater turbidity profiles to ensure optimised backwash.

5.10.2.4 Advantages and limitations

The main advantages of integrated clarification-filtration technologies are as follows:

- smaller footprint requirement, which is particularly advantageous at smaller sites with limited space;
- fully automated, minimal operator intervention is required given a single process unit;
- suits “plug and play” installations in which a packaged unit is delivered to site and can be connected to existing site services, often with minimal installation work required.

The following limitations are presented:

- There is no distinct monitoring point available to measure coagulation and clarification performance. Any issues with these processes will have a direct impact on the filtration process.

- In DAFF it is not possible to visibly inspect the filter media bed owing to the presence of the DAFF sludge blanket.
- Any issue will require full process shut-down of both clarification and filtration.
- Water throughput from the process unit will cease during backwash. If the unit is the only on-site treatment, this will stop production from the DWTP entirely for the duration of the backwash. Downstream flow balancing is required to manage this.

6. GRANULAR ACTIVATED CARBON

6.1 Process Overview

Physical adsorption is a process in which solute molecules (adsorbate) become attached to a solid surface under the attracting influence of surface forces (van der Waals forces). This is primarily a surface phenomenon. Good adsorbents have a very high specific surface area that is relatively free of adsorbed materials (they are said to be "active" or "activated"). Many organic materials found in water can be removed by adsorption. Hydrophilic substances and ions are not amenable to removal by adsorption. In drinking water, activated carbon-based media are some of the most effective and cost-effective technologies available for adsorption-based treatment.

In drinking water treatment, activated carbon is utilised in one of two forms:

1. as powdered activated carbon (PAC), which is dosed typically upstream of coagulation and clarification;
2. as GAC media, which are used as media in rapid gravity or pressure filters.

Although the adsorption mechanism applies equally to both PAC and GAC, it is considered that GAC is a specific application of rapid gravity or pressure filtration that uses activated carbon media. Therefore, the guidance provided in this chapter applies only to GAC applications.

Activated carbons suitable for water process applications are produced from a variety of raw materials, including bituminous coal, lignite, peat, petrol coke, wood and coconut shells. The production process involves the pyrolysis of the source material, during which the volatile components are released and the carbon realigns to form a porous structure.

GAC allows a more complete use of the adsorption capacity of the carbon, thus reducing overall treatment costs. GAC beds provide a filtration capacity as well as an adsorption function. GAC is easier to handle than PAC, requiring to be replaced (or regenerated) only when its adsorption capacity is reached.

The general process overview is as described in Chapter 5 with the key elements including the following;

- **Forward filtration**: water flows through the filter media at the rate required to ensure that the minimum EBCT (see section 6.3 below) is maintained.
- **Backwash**: whereas primary rapid gravity filters and pressure filters are backwashed with either a sequential air–water wash or a combined air–water backwash, GAC adsorbers will be washed using a water-only wash, or sequential air–water wash. Air scour can be installed also but can be omitted where the feed water is known to be of very high quality, such as a very high-quality groundwater source.
- **Return to service**: slow start or run to waste is used as per the recommendations of section 6.4.
- **Media replacement**: the GAC media are removed from site and replaced with virgin carbon.
- **Regeneration**: the GAC media are removed from a site and transported to where it is cleaned and re-activated by a chemical or a thermal process. The media can then be returned to site and re-installed into its original adsorber, with a top-up of new virgin media as required.

The major difference between GAC media and sand and anthracite is the definitive, limited capacity of GAC media for adsorption, meaning that such media no longer have active capacity to adsorb the target compound for removal. The capacity cannot be restored by backwashing and therefore media are considered exhausted at this stage and must be either completely replaced or regenerated. Use of regenerated activated carbon within the water treatment industry in Ireland is rare, but this may change in the future.

The exact life cycle of activated carbon media to provide effective adsorption depends on numerous factors including water quality and target compounds for removal. However, a working life of 9–18 months is a typical range. Working lives of up to 48–60 months can be possible depending on the frequency and concentration of the element(s) to be removed in the feed water.

GAC media are very porous and, in addition to adsorption applications, they also provide excellent filtration for general solids removal and can be used for primary filtration applications and general turbidity reduction. The use of GAC media for rapid gravity filters and pressure filters can be less advantageous owing to the requirement for frequent backwashing and aggressive air scouring. GAC media are not as robust as sand or anthracite and are susceptible to breakdown, especially from the air scour phase. GAC use in Ireland is predominantly for specific adsorption applications targeting taste- and odour-causing compounds, natural organic compounds and synthetic organic chemicals (i.e. pesticides). It is unlikely to be whole-life cost-competitive compared with conventional filter media for turbidity removal.

The efficiency of a GAC process relies on three key factors:

1. the type of activated carbon media used;
2. the targeted pollutant(s) to be removed;
3. the design and operating conditions, including feed water quality characteristics.

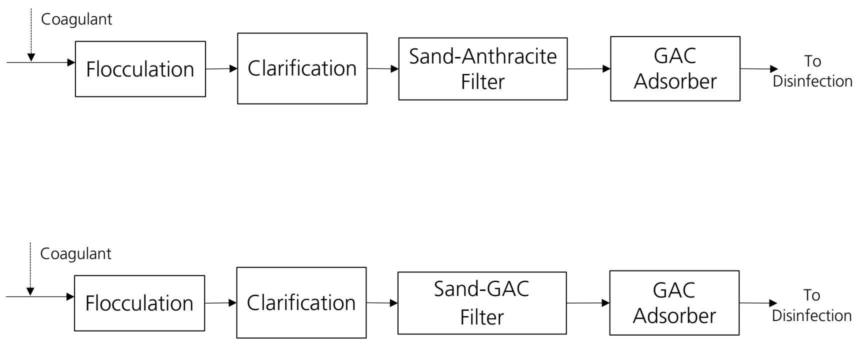
6.1.1 Filtration objectives

GAC media are used in drinking water as follows:

- as the media bed (in its entirety or as a distinct layer) in rapid gravity filter or pressure filter applications to provide additional removal for certain organic compounds, chlorine and its by-products;
- as a second stage (separate) filter, referred to as a GAC adsorber, consisting entirely of a GAC media bed.

An example of a typical DWTP using GAC is depicted in Figure 6.1.

Figure 6.1: Use of GAC media in drinking water typical process trains.



GAC media are used in other countries (i.e. New Zealand, Canada, United States) for targeted biologically active filtration (BAF). This is not currently practised in Ireland, but an outline of the basic principles is provided in Chapter 10 for reference.

GAC is used to meet the following objectives:

- **Organics reduction**: GAC media are used predominantly for the removal of certain organic compounds, most commonly as the general removal of chlorine and its by-product (DBP) precursors, removal of taste- and odour-causing compounds and micropollutants (e.g. pesticides, algal toxins, synthetic organic compounds).
- **General turbidity reduction**: although rarely a primary objective, GAC media are very effective filtration media and will provide removal of suspended solids. GAC media are not generally selected for conventional rapid gravity filters and/or pressure filters as they have a shorter effective working life than sand and anthracite. If the feed water to the filters contains significant amounts of suspended solids, filtration ahead of the carbon bed will help to improve its working life.

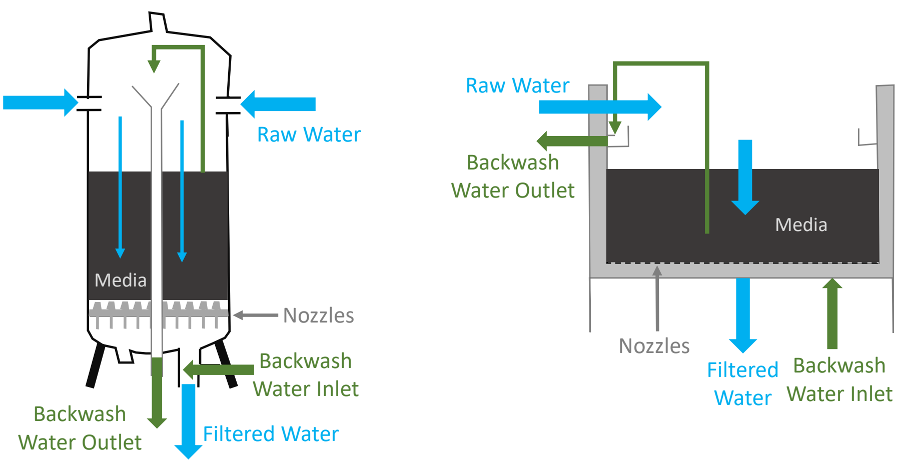
6.2 Process Equipment and Layout

The equipment and layout outlined in Chapter 5 also apply to GAC adsorbers, which are either open-topped gravity bed filters or contained within pressure vessels, both where the GAC media are provided in an independent vessel and where GAC is installed as a layer within a conventional dual- or multi-media filter.

Some additional guidance specific to GAC adsorbers is provided as follows:

- **Media bed**: it is common for GAC beds to be deeper than primary filter beds. The depth of bed will be dependent on the required contact time of the water with the media. Depths of 2–3 m are not uncommon.
- **Consideration for media removal and installation**: owing to the need to regularly remove and refill with new media, GAC adsorbers will also have built-in equipment to facilitate the transfer of media in and out of the vessel. These typically involve an eductor water-based system, or impeller centrifugal pumps.

Figure 6.2: Layout of activated carbon.



(Image provided by Enva Ireland)

6.2.1 Considerations for selection of activated carbon media

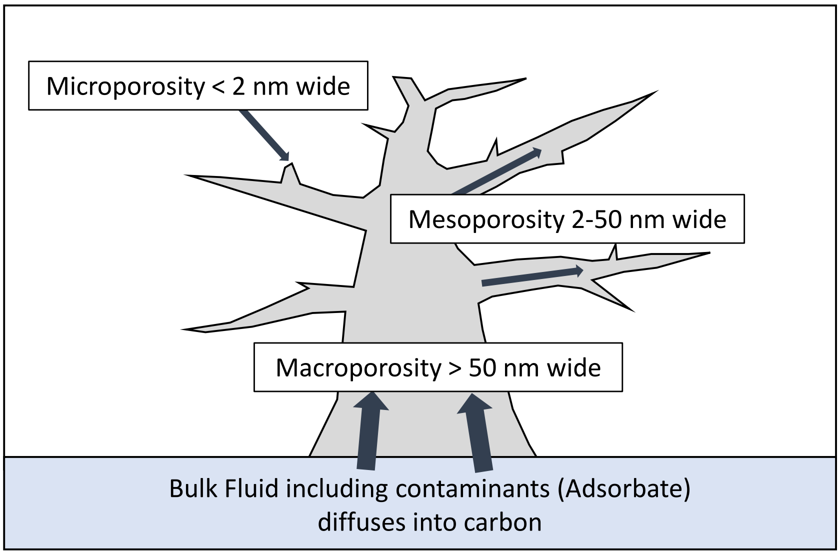
GAC media are derived from organic materials with a high carbon content including coal, carbon, peat, wood and coconut. The media are engineered with different products recommended for different target applications. Coconut and coal are the most common forms used in drinking water treatment. Generally, the best product is selected in direct consultation with the media supplier and is entirely dependent on the target compound(s) and water quality. Bench-testing can be carried out to help select the optimal product if required.

The presence of other adsorbates in the water, as occurs in most practical cases, would affect the adsorption capacity of the activated carbon for a specific compound, even if the water contains only weaker adsorbing compounds. Therefore, it is recommended that a GAC isotherm be developed to determine the most effective activated carbon media for a specific application. Pilot plants can be operated to verify the extent of specific material removal from the drinking water and confirm the necessary EBCT (refer to section 6.3) to achieve the limits of the relevant drinking water standards.

Some considerations for media selection include:

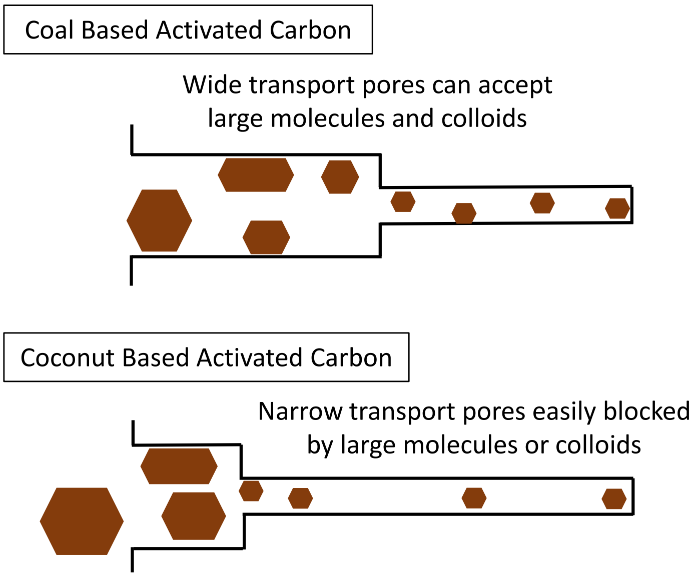
- **Pore size and structure**: pore size is generally given by the size [angstroms (Å) or 10^{-10} m]. Carbon used for drinking water falls into three categories: macroporous (> 1000 Å), mesoporous (100–1000 Å) and microporous (< 100 Å). Each type of GAC media will contain a range of pore sizes and structures. Generally, macropores are required for general TOC (colour-causing compounds) whereas micropores are required for pesticides and specific organic compounds. Activated carbon filters with dense pores < 2 µm can filter out *Cryptosporidium*. Refer to Figure 6.3 for an illustration of the 'tree root' pore structure of activated carbon. Figure 6.4 illustrates how pore structure differs between carbon media types. It is important to select the pore size and structure that best targets the compounds required to be removed.
- **Iodine number**: a standard measure of the surface area (or adsorptive capacity) of the activated carbon. It is defined as the number of milligrams of iodine absorbed by 1 g of carbon under controlled test conditions. Most GAC media used for water treatment will have an iodine number in the range of 600–1100. Iodine number is an effective metric to express micropore capacity. As GAC is used at a DWTP, the iodine number will decrease.
- **Molasses number**: an index of the porosity of GAC to larger molecules in the mesopore and macropore range (> 20 Å). This is a standard laboratory measure that reflects the potential pore volume in carbon that is available to adsorb larger molecules. On the European measurement scale, GAC will typically have a molasses number of 110–525.
- **Media size**: the media size required is dependent on the process objectives. When GAC is used within a primary filter, the size of the GAC media selected should be in accordance with the recommendations in Chapter 5. This is because these filters are also used to ensure an adequate barrier to pathogens, and therefore a suitable L/D ratio must also be provided across the depth of the media bed. When GAC is used in second-stage filters, the media size is typically larger and more variable, usually ranging from 0.6 to > 1.5 mm.

Figure 6.3: "Tree root" structure of activated carbon.



(Image provided by Enva Ireland)

Figure 6.4: Example of pore structure for different carbon media types.



(Image provided by Enva Ireland)

6.3 Design Considerations

The following design parameters are critical and should be considered when selecting GAC adsorbers:

- **EBCT (min)**: the EBCT is simply calculated by dividing the available empty bed volume (m^3) by the flow rate through the carbon. It is a design parameter that is selected to avoid breakthrough of the target compound(s) over the design life of the carbon media. The optimum EBCT is usually determined in the preliminary design phase, and facilities are sized to achieve the desired EBCT at the maximum design flow rate for a DWTP.

- The EBCT is the most critical design parameter for sizing an adsorption GAC treatment process because it affects both the size of the process and the efficiency of its operation. Generally speaking, EBCT will not be less than 10 minutes and can exceed 30 minutes for more challenging compounds (i.e. pesticides).
- **Filtration rate (m/h)**: the filtration rate is dependent on the desired application. When used for primary filtration, the loading rates are within the range quoted in Chapter 5. When adsorption is the primary objective, loading rates up to 15 m/h are typical. For adsorption applications, the loading rate will largely be a function of the target EBCT as this governs the required hydraulic retention required within the vessel.
- **Process redundancy**: the design must ensure that there is sufficient filter capacity (number of filters and available surface area of filtration media) that the maximum allowable filtration rate is not exceeded when filters are out of use for repair, backwash and media replacement, which can result in, at a minimum, several days' downtime.
- **Media bed depth**: media depth is usually dependent on the design EBCT for the filters. Depths of up to 2.5 m (gravity applications) and 3 m (pressure filters) are typical in adsorption-based applications.
- **Backwash type**: GAC adsorbers should be installed with backwash systems to maximise the working life of the GAC media. Some facilities may choose to replace media at more frequent intervals in lieu of installation of a backwash system. Media from these installations lacking in backwash facilities are not suitable for regeneration. GAC filters are typically backwashed with a sequential air–water cycle as outlined in Chapter 4, to target approximately 20–30% bed expansion. Installations with very high-quality groundwaters with low solids loading may not include an air scour.
- **Bed life**: depending on the targeted compound(s) for removal it may be useful to complete benchtop column tests to understand the potential design life of the GAC media for a particular application.
- **Backwash flow rate**: temperature compensation can be considered to ensure that adequate bed expansion is maintained across all seasonal temperatures, while safeguarding against any loss of media from the adsorber as a result of greater bed expansion experienced during colder temperatures when water viscosity is at its maximum.
- **Physiochemical properties of feed water**: temperature will have an impact on adsorption mechanisms. In warmer water, adsorption will be less effective. Adsorption is also affected by pH as it determines the charge density of the organic material and affects absorbability, i.e. low pH will favour the adsorption of acids and alkali conditions will favour the adsorption of bases.
- **Target compound(s) for removal**: the required EBCT and expected media life as outlined above are highly dependent on the physical and chemical properties of the targeted compound(s). Some general rules are as follows:
  - High molecular weight, high boiling point, low water solubility and high octanol–water partition coefficient (K_{OW}) are associated with high adsorptive capacities.

- High polarity, a large number carbon atoms and a large number of double bonds are associated with low adsorptive capacities.
- Organic compounds are typically more adsorptive than inorganic compounds.

6.4 Guidance on Operation

The guidance below applies to GAC adsorbers and provides general considerations for managing the life cycle of GAC media. For installations in which GAC is part of a primary rapid gravity filter or pressure filter application targeting pathogen removal, please refer also to the guidance in Chapter 5.

6.4.1 Forward filtration

The main objective of forward filtration is to ensure that there is sufficient adsorptive capacity within the media (i.e. no breakthrough is occurring) and that the GAC adsorbers are backwashed sufficiently to minimise the impact of any biological growth.

Head loss is typically measured on each individual vessel. Individual turbidity monitors should be installed when the adsorbers are being used for the additional objective of enhanced turbidity reduction as a barrier against protozoa. The majority of applications in Ireland are unlikely to require this. Combined turbidity measurement post-GAC adsorbers should be installed in all instances.

6.4.2 Backwash and return to service

The frequency of backwashing required for second-stage GAC adsorbers is significantly less than that needed in primary filtration applications. However, second-stage filters at surface water treatment plants may require more frequent backwash to dislodged accumulated solids within the filters. Consideration should be given to installing an automatic backwash trigger for head loss, especially at DWTPs treating surface water. Some facilities, especially those where GAC adsorbers were retrofitted into an existing treatment facility, may not have any facility for backwash and rely on more frequent media replacement to manage this risk.

Typically, GAC backwash frequency 2–8 weeks at high-quality groundwater sites and up to several times per week at surface water sites. This is because of the higher solids loading and more biologically active source water from surface water sources. The main objective of the backwash is to control biological growth, particularly of microorganisms. Organisms of particular concern include zooplankton and chironomid larvae, which can sustain populations within a GAC. Backwashing can be an effective control measure if carried out at a frequency shorter than the life reproductive cycle of the organism, e.g. every few days. These organisms are visible to the human eye and if allowed to populate the GAC adsorber can reach the customer’s tap.

It can be considered best practice to avoid backwashing GAC adsorbers with chlorinated water. However, many water treatment plants will backwash with chlorinated water. It is important to be aware of the associated risks and consider that the potential working life of the media may be reduced if chlorinated water is used as a backwash source.

Free chlorine is reduced to chloride in a reaction at the GAC surface. The reaction is very fast and occurs in the first few minutes of EBCT. Continuous exposure to chlorine can result in degradation of the GAC structure and will produce more fines and GAC losses over time. The chlorine may also react with organics adsorbed on the GAC surface, creating potentially undesirable by-products that may desorb into the finished water.

Combined chlorine also reacts with GAC in manner similar to free chlorine. However, free ammonia will be released into the system as the ammonia is not destroyed. Free ammonia may affect downstream chlorination chemistry and possibly result in nitrification in the adsorber.

Backwash for removal of accumulated solids is still important, and the guidance presented in Chapter 4 should be applied to GAC adsorbers. However, backwash for biological control usually needs to be much more frequent than what would be required for solids removal.

6.4.3 Return to service from backwash

Similar to the process outlined for rapid gravity filters and pressure filters in Chapter 4, there is a required ripening period when returning a GAC filter to service. The vessels are typically run to waste at the target flow rate for one to two bed volumes and/or until suitably filtered turbidities are observed. It is common to dislodge fine suspended solids and any residual fines within the GAC media during the backwash.

Older installations or those at sites with constraints on process residuals treatment might have a slow start methodology, where the flow rate is slowly ramped up over a set time interval (typically 30–60 minutes) in line with the consideration for allowable percentage rate of change outlined in Chapter 4. Particular care must be given to downstream disinfection processes (i.e. chlorine contact tanks) with a maximum allowable turbidity requirement. Any elevated turbidities when vessels are returned to service can have an impact on these treatment processes if not sufficiently mitigated.

6.4.4 Media replacement and media regeneration

In Ireland, GAC media beds are generally replaced with 100% virgin media when the adsorptive capacity of the media has neared exhaustion and bed replacement is required. GAC regeneration is widely implemented across the United Kingdom and it is expected that this practice will eventually become preferable to constant media replacement as GAC use increases in Ireland.

The basic process for regeneration is as follows:

- GAC media are backwashed and removed from adsorber.
- GAC is transported to regeneration facility.
- GAC is regenerated through thermal and/or chemical activation process.
- GAC is returned to site.
- GAC is re-installed in adsorber and topped up with virgin media.
- GAC vessel condition is completed before returning the filter to service.

6.4.5 Return to service following media replacement

Virgin media can contain contaminants such as metals, aluminium, iron, manganese, etc., that could leach into the filtrate when an adsorber is brought online. Media that have been returned from regeneration can also contain compounds that were adsorbed to the media and not fully removed or converted in the reactivation process. Potential issues to be aware of include:

- **Metals (aluminium, iron, manganese, coppers)**: can cause high metal levels and potential discoloration in filtrate.
- **Alkali compounds**: can cause high pH from filtered water.
- **Sulphides, sulphites and bisulphites**: can generate chlorine demand and taste and odour issues.
- **Phosphates**: when chemical regeneration by phosphoric acid has been completed.

More detailed guidance is provided in section 6.8 on process start-up and shutdown.

There are some packaged solutions currently available in the Irish marketplace that are considered "plug and play" solutions. These systems can be installed at small sites with the benefit of being pre-conditioned at a central facility before deployment to site. This allows most of the backwash and forward rinse, required to remove fines from virgin media, to be done before the unit is delivered to the DWTP.

In these installations, consideration must be given to any differences in water quality for the water used to condition the virgin media, especially pH, which has an impact on adsorption and metal solubility. When conditioning is completed at a different pH and/or flow rate, it is possible that there will be some further leaching of compounds of concern while equilibrium is restored within the adsorber. In these cases, some on-site backwashing and forward rinse with sampling is recommended. These units will be replaced as required prior to the adsorptive capacity of the adsorber media becoming exhausted.

Figure 6.5: Example GAC "plug and play" installation.

(Image provided by Enva Ireland)

6.4.6 Anaerobic conditioning

When microorganisms or micro-animals have accumulated in the GAC reactor, one way to remove the biological activity is to implement an anaerobic conditioning period. Removing a GAC adsorber from service and allowing anaerobic conditions to develop should lead to death of the microorganisms. The water level must be maintained above the media bed and the process typically takes about 5 days to complete. Time must be allowed for the formation of ammonia and nitrite in the filter from natural biological processes. Care must be taken in returning the vessel to service, as outlined further in section 6.8.

6.5 Process Optimisation

The following parameters can be considered for process optimisation:

- **Media replacement frequency**: operational monitoring is often difficult to complete given that there is limited scope for on-site tests, and laboratory testing can be very costly for the majority of targeted compounds (i.e. pesticides and other synthetic organic compounds). However, regular sampling of individual adsorbers and the combined filtrate can be useful in understanding the breakthrough curve and maximise the use of the media bed. The use of continuous online UVT monitoring can also be beneficial for some applications, particularly those targeting colour and general TOC reduction.
- **Media age**: it can be helpful to stagger the age of the adsorber beds. This will allow for staggered media replacement and also reduce the risk of breakthrough having an impact on final water quality targets. As media replacement can constrain site operations owing to demand for water and the volumes of wastewater produced, staggering replacement can minimise the impact on DWTP operations.

6.6 Critical Control Parameters

The identification of critical control parameters is an important aspect of applying the DWSP methodology. Table 6.1 summarises the recommended critical control parameters and associated control measures for GAC. This list should not be taken as exhaustive, but should be used as guidance as part of the DWSP development for a site.

Table 6.1: Critical control parameters for GAC adsorbers

Critical control parameter	Significance	Recommended control
Feed water turbidity	It is important to measure the feed water turbidity at the same frequency as the post-GAC adsorber filtered water turbidity to confirm that there is no unexpected solids loading in the GAC of as a result of suboptimal upstream performance. An increase in turbidity can also be an indication of biological activity within the GAC media bed	Continuous online turbidity monitoring

Critical control parameter	Significance	Recommended control
Individual filtered turbidity	Identifies any issue with an individual filter. Although a beneficial tool, individual monitors are required only when the adsorbers are used for enhanced turbidity reduction for pathogen removal. Most installations will be downstream of a first-stage filter and will not require individual monitors	Continuous online turbidity monitoring
Combined GAC filtered turbidity	At surface water treatment plants this is required monitoring as it is typically the last process that has an impact on the turbidity requirement for downstream disinfection processes (i.e. chlorine disinfection, UV disinfection)	Continuous online turbidity monitoring
Media replacement frequency	Media must be removed and replaced (or regenerated and returned to site) to avoid breakthrough of the target compound(s) for removal	Operational procedures
EBCT	The EBCT is a design parameter and is application specific but typically will range from 15 to 30 minutes As the media bed is fixed, the EBCT is maintained by ensuring that the flow throughput through the vessels does not exceed the allowable limit to maintain the EBCT	Continuous flow rate monitoring Operational procedures for units out of supply
Bed depth	To maintain the EBCT it is important to maintain the bed depth. GAC is more susceptible to breakdown from backwashing and loss of media is expected to occur more rapidly than with sand and anthracite filtration applications	Operational checks
Head loss	Head loss across each individual adsorber should be measured. A backwash trigger could be considered as an additional safeguard	Continuous online head loss monitoring
Organic concentrations (e.g. TOC, trihalomethane, pesticides in the filtered water)	Regular sampling and testing of the filtered water exiting the GAC adsorber. High concentration in the filtered water might be an indication of media exhaustion This should be completed in conjunction with regular raw water monitoring to confirm the feed water loading UVT monitoring may be a suitable control for sites where general TOC removal is targeted for management of DBPs including THMs or general colour removal. UVT will not be sufficient for more advanced applications including pesticides removal and enhanced TOC reduction	Grab sampling Continuous online UVT monitoring (if appropriate for application)

6.6.1 Guidance on log removal credits

For facilities operating on the turbidity performance approach, turbidity following primary filtration should be maintained below 0.2 NTU to safeguard downstream disinfection processes.

A 0.5 log credit for protozoa can be claimed only for GAC adsorbers that are second-stage filters, meaning that there is an upstream conventional (RGF or pressure filtration) filtration process.

The log credit can be achieved if the following criteria are achieved as a minimum:

- All water must pass through the upstream coagulation and filtration process and the second-stage filters.
- Continuous turbidity monitoring is provided for each individual adsorber and combined filtered water
- The following turbidity performance criteria are achieved from each individual vessel and total combined filter filtered water:
  - turbidity does not exceed 0.15 NTU for 15 consecutive readings;
  - turbidity does not exceed 0.3 NTU for more than 15 consecutive readings
  - turbidity does not exceed 0.5 NTU for more than three consecutive readings.

6.6.2 Regular operational checks

Operational checks as outlined in Table 6.2 are recommended.

Table 6.2: Recommended operational tasks for GAC adsorbers

Task	Description	Recommended frequency
Backwash observations	Visual inspection of the backwash. Sampling of the used washwater should be completed every minute during the backwash to confirm the absence of any significant GAC fines, which could indicate excessive air scour and/or backwash rates. Turbidity can also be measured to confirm removal of any accumulated solids	Monthly to quarterly
Media coring	A sample of media should be taken from the media bed to inspect for poor media condition	Once per annum
Backwash expansion	The backwash expansion should be measured twice annually to capture the warmest water temperature (minimum expansion) and coldest temperature (maximum expansion) The exercises should be repeated on multiple filters, and performed for each backwash pump, where a duty standby arrangement is in place. This may not be possible for pressure filters	Twice per annum
Filter outlet valves	Filter outlet valves should be tested to confirm that they are fully functional and do not allow water to pass forward when in the shut position	Annually
Filter media integrity	Samples removed from the filter bed should be sent for sieve analysis to confirm the UC. This should be completed when the GAC media bed is older than 2 years	As required (> 2 years of age)

Task	Description	Recommended frequency
Media depth check	The depth of media should be measured, or a datum point available in the filter to confirm that minimum bed depth is maintained	Quarterly

6.6.3 Operational records

In additional to the monitoring data available from online instrumentation, it is recommended to ensure that all operational logs and recorded information as a minimum capture the following information:

- the date media was installed in each adsorber, full details of the product name, supplier, base material, sieving, ES, UC, iodine number, as listed in section 6.2;
- records of water-quality tests completed prior to an adsorber with recent media replacement re-entering supply;
- records of any media depth checks, including an assessment of estimated percentage loss;
- the number of adsorbers in service and the filtration rate(s);
- raw water and upstream filtered and final water quality (on-line instrumentation and onsite testing records) including water temperature;
- details of any incidents, unusual events or notable observations with respect to raw water quality (i.e. algal blooms, severe weather events, pH fluctuations, etc.).

6.6.4 Guidance for media checks

Media samples can be sent for sieve analysis to determine the UC to compare it with that of the original virgin (unused) media. An increase in the UC can indicate that there are increased "fines" present and that some degradation of media has occurred. A decrease in ES also indicates that media degradation has occurred.

Where the capacity of the GAC media and the expected bed life are unknown, completion of an iodine test can be considered on installed media. These tests do not mimic real life capacity but can give a good indication of whether or not the adsorptive capacity of the pores is still within the recommended range.

6.7 Upstream and Downstream Considerations

6.7.1 Process inputs

The following inputs are required to support the GAC process:

- **Backwash water**: water for backwash is often sourced immediately after the GAC adsorber, often before any downstream chemical (i.e. chlorine) addition. However, some treatment plants will use final treated water as the source of the backwash, but care should be taken to ensure that the backwash water pH does not differ significantly from the operating pH range of the adsorber. If there is chlorine in the backwash water, consideration must be given to the disposal of chlorinated wastes from the water treatment plant. However, GAC media will readily adsorb chlorine, and there is unlikely to be a significant chlorine residual after filter backwash.

6.7.2 Process residuals

The following process residuals are produced by GAC adsorber:

- **Dump volume**: gravity filters can be drained into supply or into waste; however, adsorbers that are pressure filters must be drained to waste.
- **Used backwash water**: the volume produced is usually equivalent to approximately two to three bed volumes. Backwash water may require some settlement for solids removal. It is important to ensure that there is sufficient capacity to allow for all filters to be backwashed under worst-case operating conditions without being constrained by insufficient capacity for settlement of the waste washwater.
- **Run to waste**: waste from the filter run to waste is either disposed of (sewer or to natural environment) or is returned to the head of the DWTP after treatment. In these cases, a minimum quality (usually turbidity and metals residuals) is recommended. The water should be returned upstream of any coagulant dosing.
- **Media replacement washing requirements**: significant wastes can be produced during media replacement, when frequent backwash and run to waste can be required. These washes can be staggered over several days to minimise the impact on process residuals systems.

At surface water sites, GAC adsorbers will often be retrofitted into DWTP with existing primary-stage filters. It is important that these systems have sufficient capacity and that backwash requirements for one process do not have an impact or inhibit on another. It is often preferred to have independent backwash systems for each filtration stage.

Any water discharged back to watercourse must receive adequate treatment to comply with any regulatory requirements and ensure that there is no impact on the receiving water body.

6.7.3 Upstream considerations

In the event of suboptimal performance upstream, GAC adsorbers can be an effective filtration barrier against elevated turbidities. If a period of poor upstream performance is realised, the GAC filters should be backwashed as soon as possible.

Additional considerations as follows:

- There are no significant pH fluctuations that could cause de-adsorption from the bed.
- The impact of algae in the source water is minimised. Algae can have an impact on the required backwash frequency and cause changes to the normal pH profile within a water treatment plant. Decaying algae can also cause taste problems and reduce the adsorption capacity of the bed.

6.7.4 Downstream considerations

Backwash water must be sourced from downstream of the filters. Diverting water for backwash requirements can have an impact on flow (and flow measurement). This can have a negative impact on downstream processes, especially chemical dosing control at plants where chlorine is dosed immediately after the filters.

Backwash wastewater and wastes from the dump volume and run to waste require further treatment prior to either recycle to the head of the DWTP or discharge to sewer or local watercourse. Poor management of backwash cycles or media replacement for GAC at the DWTP can put strain on these processes.

6.8 Process Start-up and Shutdown

6.8.1 Return to service after refill or long-term shutdown

The following guidance applies to returning a GAC vessel to service after media replacement:

- Perform an extended backwash to remove fines from the media. The target should be achieving < 10 NTU in the backwash water. It is not uncommon for over six bed volumes of washwater to be required.
- It is recommended that the media depth be measured to confirm the total bed volume provided. Drain down may be required.
- Implement a forward rinse at a rate similar to that at which the vessel will be returned to supply.
- Carry out on-site testing to confirm that the pH from the vessel is acceptable. General metals (iron, manganese, aluminium) and chlorine demand can also be useful for comparison. The test should be carried out on the run to waste water and used to determine if a vessel is ready to re-enter supply.
- If the media received any offsite conditioning, it may be necessary to carry out an extended forward rinse or repeat the backwash and forward rinse. Conditioning refers to any washing or chemical soaks that might have been completed before delivery to site.
- All modern GAC installations should have the capacity to run forward rinse to waste. If this facility is not provided, additional backwashing may be required in combination with a controlled slow-start methodology.

6.8.2 Return to service after regeneration

The requirements for returning to service after regeneration are slightly more onerous owing to the risk of leachable material that was not fully removed during regeneration will affect filtered water quality. In these instances, a more extensive forward rinse of up to 20–30 bed volumes can be required.

Water quality testing should be carried out on the vessel to be returned to service and on an additional comparison vessel. Recommended parameters include at, a minimum, pH, odour and metals (Al, Fe, Mn).

6.8.3 Long-term shutdown and start-up

Some applications of GAC adsorbers may involve targeting a compound of concern that is present only seasonally. This strategy can be effective and has been used in North America to deal with seasonal issues such as the presence of the taste-causing compound geosmin. The plant operator therefore may consider shutting down the GAC absorbers when they are not required. The following guidance is provided in the event of such a situation:

- The unit should be backwashed prior to removal from service.
- If it is to be left offline for a significant period of time, the adsorber should be backwashed and then fully drained. If the media bed is left flooded, the bed will turn anaerobic and this will lead to the presence of ammonia and nitrite.
- Before being returned online, the filter should receive an extended backwash.

6.9 Process Troubleshooting

A particular challenge to GAC adsorption is that many of the target compounds are not available for rapid testing, with the result that an issue might not be not identified until a sample is taken for general regulatory compliance or operational surveillance monitoring. Owing to the expense and challenge of testing, it is not often feasible to monitor frequently for the target compounds of interest, especially from individual adsorbers when multiple units are present.

For guidance related to issues with filter and media condition, please refer to the guidance provided in Chapter 5**.**

A review of potential issues, areas of investigative action and potential corrective action has been provided for GAC adsorbers in Table 6.3. These identified issues should not be considered exhaustive but should be used to develop local operational procedures.

Table 6.3: Malfunction: source water challenges and upstream process quality change

Issues	Recommended investigative action	Potential corrective action
Micro-animal population established in GAC vessel	Confirm if all vessels are affected Review backwash frequency and duration. Increase if required	Consider anaerobic conditioning of affected vessel(s)
Exceedance of target compound(s) for removal in GAC adsorber	Review raw water and final water sample data. Is the challenge attributed to increased raw water loading? Complete investigative sampling, including sampling oldest GAC media bed(s) in addition to combined filtered GAC Review to check if EBCT requirements are being met Confirm if breakthrough is from GAC adsorber	Consider flow reduction as short-term measure to increase achieved EBCT Arrange for GAC media replacement (when breakthrough is confirmed)
Turbidity increasing post-GAC compared with upstream levels	Review flow trends – has there been any hydraulic shock to the adsorbers? Confirm if issue is related to single vessel or if all adsorbers are affected equally Visually inspect filtrate for any evidence of micro-animals Review upstream process performance. Has there been any disturbance to the pH profile?	Complete backwash with consideration for extended backwash Complete upstream corrective action required

Issues	Recommended investigative action	Potential corrective action
Unable to achieve filtered turbidity target of < 10 NTU in washwater after media refill	Complete an additional extended backwash followed by extended run to waste Consider testing media to ensure that it is within the target specification for UC and ES.	Additional backwashing and/or run to rinse should resolve majority of issues. Specialist consultation with media supplier may be required.

6.10 Advantages and Limitations

Advantages are as follows:

- Can be retrofitted into existing primary filtration assets with minimal investment required.
- Can provide effective reduction of DBP precursors and for many synthetic organic compounds including pesticides.
- Can be more whole-life cost competitive compared with PAC (a continuous direct feed system which requires processing with the sludge stream at a DWTP) owing to its continuous nature.
- Secondary filtration adsorbers can provided enhanced turbidity removal to benefit downstream disinfection.
- "Plug and play" installations can be used with lower infrastructural cost/ fewer operational risks due to ability to complete most required installation and commissioning work offsite.
- Water analysis can be completed to identify and select the most adapted type of activated carbon for a particular application.

Limitations are as follows:

- Media capacity can be exhausted within several months for some challenging pesticides. When the regeneration of media is not an option, this can add significant cost to the operation of GAC.
- Can place a strain on sites with respect to the provision of backwash water and plant residuals treatment and processing when retrofitted into an existing treatment process.
- Biological activity specifically with respect to microorganisms can be a seasonal challenge and require operationally intensive anaerobic conditioning to be completed.
- Operational monitoring of target compounds for removal is often expensive.

7. CARTRIDGE AND BAG FILTERS

7.1 Process Overview

Cartridge and bag filters are pressure-driven separation devices that remove particles using engineered porous filtration media (US EPA, 2010). Bag filters are typically non-rigid fabric-based media. Cartridge filters are typically rigid or semi-rigid material, typically constructed of polymer or fabric that is attached to a central core structure.

Both technologies are contained within pressure vessels.

The general process overview for both technologies is listed below:

- **Filtration**: as water passes through the filter element, solids will accumulate on the surface and within the structure of the filter media. This results in a pressure decrease across the filter.
- **Replacement**: the filters are designed for a maximum allowable pressure drop, which is referred to as terminal pressure. Once this pressure drop has been reached, the filter element must be removed and replaced with a new unit, but in practice the filter is replaced long before this is achieved because as the filter blocks the flow declines significantly, making further use impracticable.

Typically, there is no backwash associated with bag or cartridge filtration. Source water quality will have an impact on the lifespan of the filters and where the raw water (or upstream) turbidity is relatively high it may not be an economically viable option. Different kinds of particulates, such as finer sized colloids and clays, may also make the source water unsuitable for this kind of filtration technology.

The key physical filtration mechanism is straining, such that any particulate material larger than the filter media pore size will not pass through the filter element. It should be noted that filters are defined not by the size of their pores, but by the size of the particles they are capable of removing. As an example, a 1 micron (μm) filter may have pores that are > 1 μm but be effective at removing particles 1 μm in size.

Figure 7.1: Example of cartridge and bag filters.[3]

Cartridge filters

Bag filters

3 (Pennsylvania Department of Environmental Protection, 2017a).

7.1.1 Filtration objectives

Bag and cartridge filters are generally found only at small to medium water treatment plants; however, they are increasingly being used at larger facilities with current use exceeding plant size of 50 MLD in the United Kingdom. Owing to the replacement requirements and limits on vessel size, the technology may not be cost-effective for larger water treatment plants.

Bag and cartridge filters are used for the following filtration objectives:

- **Pre-filtration**: in Ireland, bag filtration and cartridge filtration are typically used as a pre-filtration technology. This provides general turbidity removal to protect downstream processes.
- **Pathogen removal**: currently, neither bag nor cartridge filtration are typically considered for filtration applications targeting pathogen removal in Ireland. However, in multiple jurisdictions, internationally (including the United States, Canada, United Kingdom and New Zealand) these technologies are approved for use as barriers to protozoa and are eligible for log removal credits. Because pore sizes in these technologies are not sufficiently small to provide effective removal of bacteria, viruses or fine colloidal material, only log removal for protozoa can be considered.
- Although at time of publication there are limited applications of cartridge filters in Ireland, they have been installed downstream of existing filtration processes at conventional water treatment plants to provide additional log removal or enhanced turbidity removal.
- **Residuals treatment**: cartridge filters can be used to provide turbidity removal on residuals treatment, particularly for applications that are required to meet a discharge limit, or that require a water-quality standard for turbidity as part of a recycle of a waste stream back to the head of a DWTP.

Although this technology currently has limited applications in Ireland, cartridge filters are used extensively in other countries. For groundwater sources, a 1 µm absolute rated cartridge filter may be used as a single step to control both turbidity and *Cryptosporidium*. Where water is of lower quality multiple stages of cartridge or bag filters in series can be installed, each with a different pore size. This allows a coarser pore size to remove large particles, in advance of a second stage with a smaller pore size. This can be an economical way of providing a finer level of filtration, in which feed water quality would otherwise lead to rapid clogging of the fine pores. An example of this would be a 5–10 µm upstream cartridge filter upstream of a 1 µm cartridge (to achieve log reduction of *Cryptosporidium*).

7.2 Process Equipment and Layout

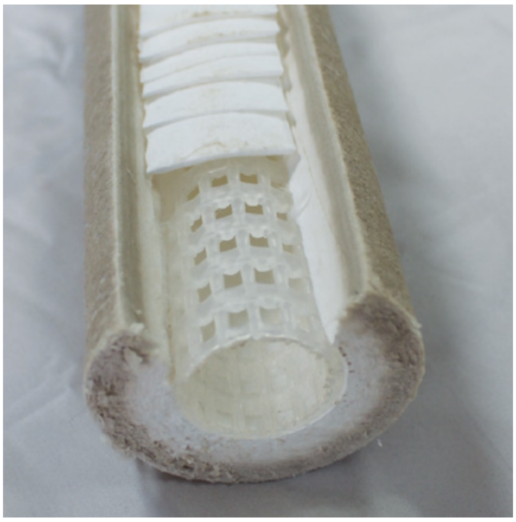
Bag and cartridge filter applications are modular systems that are sourced directly from the equipment supplier.

- **Filter housings**: each filter housing is a pressure vessel and can contain multiple filter elements (over 30 individual elements is not unusual). All water quality monitoring will be completed on each housing, rather than the individual filter components. The housing is designed to provide feed water to the system, collect the filtrate, ensure adequate water distribution across each individual filter within the housing and ensure that adequate pressure (driving force) is maintained. The main components include:

- **Housing**: typically, metal or plastic.
- **Access point**: a cap or lid to the unit that allows easy access for filter change-out.
- **Mechanical seal**: provides a seal between the lid and body of the housing. Usually in the form of an elastomeric O-ring. This seal is integral to the system and maintains sufficient pressure. This is required to ensure no short-circuiting within the unit.
- **Air release valve**: a valve should be provided to allow escape of any trapped air.

- **Filter element**: bag and cartridge filters are engineered media and the pore size is selected in consultation with the technology provider depending on the application. When disinfection for protozoa is targeted, effective pore size is usually 1 µm.
  - **Bag filters**: made from prepared fabric sheets, which are typically sewn together to form a bag. Care is given in the manufacturing process to avoid any short-circuiting during filtration through the seam. Some filters will contain multiple layers of bags, with outer layers providing coarse filtration and inner layers providing increasingly finer filtration.
  - **Cartridge filters**: generally manufactured in one of three ways. The wound technique involves winding the filter material around the central core, although this technology has limitations in removal efficiency and can be less reliable. The meltblown depth filter technique is when the filter matrix is built up using semi-solid propylene fibres. The pleated technique involves pleating the material together and fixing it within a plastic core, cage and end caps. The smaller the pore size, the higher inlet pressure is required to provide adequate driving force to force water through the filter element. An example cross-section is provided in Figure 7.2.
  - The majority of systems are of a vertical layout. Some larger cartridge filtration systems may also have a horizontal configuration.

Figure 7.2: Example cross-section of cartridge filter.



(Image provided by Amazon Filters)

7.3 Design Considerations

The following design parameters are critical to consider for bag and cartridge filters applications:

- **Feed pressure**: systems should be designed to minimise any sudden changes in pressure applied to the filters. Each time flow is interrupted, a sudden pressure increase can be caused across the unit, unless the system can be designed to allow for a gradual pressure ramp-up.
- **Upstream water quality**: any high solids loading will lead to more rapid clogging of the filter pores. Consideration should be given to any risk of biofilm growth within the media. Sodium hypochlorite (once material compatibility is confirmed) can be added upstream of the filter to control any risk for biological growth.
- **Process redundancy**: the design must ensure that there is sufficient filter capacity (number of filters and available surface area of filtration media) to not exceed the maximum allowable filtration rate when filters housing is offline for replacement or maintenance.
- **Design flow rate**: Designers should account for that fact that prolonged operation near the maximum flow capacity of the filter elements will cause the filter element to clog more rapidly than operating at lower flow rates.
- **Continuous operation**: bag filters and cartridge filters are manufactured using the wound technique are sensitive to starting and stopping, as frequent pressure changes caused by stopping and starting the treatment train can cause premature wear of the filter and shorten the life of the filter element. Consideration should be given to managing the DWTP process (i.e. installation of on-site treated water storage) to remove the need for site start-up and shutdown.
- **Filter element selection**: filters may also be rated as "absolute" or "nominal". Absolute filters are designed, validated and manufactured to provide a defined and reproduceable performance standard, whereas "nominal" filters are likely to offer variable and poorly defined performance.
- **Consideration for run to waste**: where nominal rated filters are used, frequent starting and stopping at the water treatment plant can increase filtered water turbidities. This can be mitigated by allowing for a small run to waste for the first few minutes of filter cycle, or by selecting an absolute-rated filter only.
- **Filter element life**: the expected life of a filter element (before replacement is required) will be site specific. The design life will be determined in consultation with the technology provider. Well-designed systems that provide filtration of high-quality water can exceed 18–24 months in operation before change is required.
- **Filter material**: the material and filter element should be certified to a European or equivalent standard to ensure suitability for use in drinking water applications.

7.4 Guidance on Operation

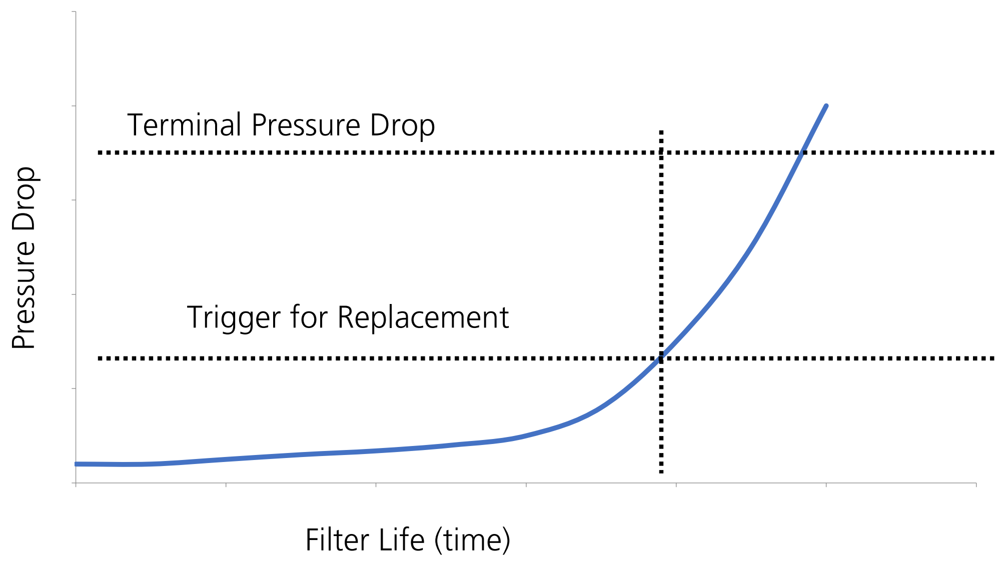
Cartridge filtration and bag filtration require minimal maintenance, with the exception of when filter element replacement is required. Guidance is provided to support operations as follows.

7.4.1 Forward filtration

The main objective of forward filtration is to ensure that there is sufficient pressure upstream of the filter, while the terminal head loss has not been exceeded.

The measured pressure drop across the filter element will be exponential in nature, which means that it will slowly increase at a linear rate and then increase rapidly before the terminal pressure is reached (Figure 7.3). Given the rapid increase of pressure, it is best practice to proactively change the filter element in advance of the terminal pressure. Head loss across a new (clean) filter element can be as low as 5–10 kPa, increasing to > 200 kPa. The exact terminal pressure will be provided by the filter manufacturer.

Figure 7.3: Example head loss profile across cartridge filter life.



7.4.2 Replacement of filter element

Air will typically be introduced into the system during filter element replacement. It is important to remove this air from the system as it can become trapped on the filter surface and reduce the available filtration area within the housing. Most commonly, it is manually bled from the system by activating the air bleed valve in the filter housing. Automatic devices are available to ensure that air is expelled from the system when present.

Where a run to waste facility is in place it should be activated following filter replacement. Many systems do not require run to waste, especially where an absolute rated filter element is installed.

When returning a filter to service, care must be taken to slowly increase the flow and avoid shock. This will likely be automated at recent installations but may require manual valve operations at older existing DWTPs.

7.4.3 Process optimisation

The main parameter targeted for removal should be the trigger for replacement of the cartridge or bag filter elements. An automatic shutdown of a filter housing, in advance of the unit reaching the terminal pressure, will probably be configured for modern systems. These triggers may be conservative. With increased familiarity with the site’s profile, it may be possible to amend this trigger and extend the working life of a cartridge. It is important to ensure that doing so does not risk the terminal pressure being reached, especially where a filter is being used for protozoa removal.

7.4.4 Critical spares

It is important to have critical spares on-site, or readily accessible, to allow for replacement of the cartridge or bag filter elements as required. The quantity of spares required to be stored on-site will be dependent on numerous factors, including:

- risk of premature clogging of filter media requiring large-scale replacement;
- the expected life of filter;
- existing on-site filter elements and the age-profile of those installed;
- the time required to source replacement elements;

Often, water treatment facilities will make arrangements with the supplier to provide additional storage and stock of the required filtered elements, with a service-level agreement to agreed timescales. It is important to consider filter storage life. Some filter elements may not be suitable for extensive long-term storage.

7.5 Critical Control Parameters

The identification of critical control parameters is an important aspect of applying the DWSP methodology. Table 7.1 summarises the recommended critical control parameters and associated control measures for cartridge and bag filters. This list should not be taken as exhaustive but should be used as guidance during the DWSP development for a site.

Bag and cartridge filters are generally monitored by indirect integrity testing, as there is no direct monitoring available to ensure that the filter barrier remains effective. Typically, critical parameters such as head loss and turbidity are monitored. Any issue with the measured parameters indicates that there is an integrity issue with the filter material. Further investigation and/or replacement is required.

The recommendations for alarms and shutdowns are based on the filter providing turbidity removal either for downstream disinfection processes or for protozoa removal.

Where the technology is provided for a less strict factor, the recommendations should be reviewed as part of the DWSP development for identifying risks and associated controls.

Table 7.1: Critical control parameters for cartridge and bag filters

Critical control parameter	Significance	Recommended control
Feed water turbidity	It is important to measure the feed water turbidity at the same frequency as the filtered water turbidity. This confirms that there is no issue within the filter housing units An alarm should be configured if filtered turbidity exceeds feed water turbidity for a duration of > 3–5 minutes	Continuous online turbidity instrumentation High-turbidity alarm

Critical control parameter	Significance	Recommended control
Individual housing filtered turbidity	This should be provided where disinfection is a target from the installed filtration processes Outlet monitoring will allow for identification of an individual housing that might have an integrity issue	Continuous online turbidity instrumentation High-turbidity alarm Process shutdown
Combined post-filtered turbidity	The turbidity should be measured from the combined process Some applications may opt for particle counting (2–5 μm) in combination with, or in lieu of, turbidity measurements A high turbidity alarm should be configured. When the high alarm threshold is achieved, the housing should be automatically removed from service	Continuous on-line turbidity or particle counting instrumentation High-turbidity alarm Process shutdown
Differential pressure (head loss)	Head loss across each housing should be continuously measured to: confirm the minimum pressure (driving) force is maintained for effective filtration ensure that the terminal pressure drop is not reached A high alarm should be configured. When the alarm threshold is achieved, the filter housing should be removed from service. The trigger will be based on manufacturer's recommendations and should be lower than that of the terminal pressure – at which point filter element replacement is recommended	Continuous online instrumentation High-turbidity alarm Process shutdown
Flow rate	The flow rate across each filter housing should be measured to ensure that the maximum rated flow is not exceeded The operational target flow rate should be less than the maximum rated flow rate for the units, to maximise the life of the filter element An alarm should be configured when the allowable flow rate to a housing is obtained. This should occur with an automatic process shutdown if flow through any housing exceeds the allowable maximum	Continuous online instrumentation Process alarm Process shutdown

Critical control parameter	Significance	Recommended control
Filter age	As per manufacturer's recommendations, each filter element may have a maximum life for which integrity of the filter is guaranteed. Filter elements should be changed in line with this guidance, when protozoa removal is a targeted application	Operational procedures

7.5.1 Guidance on log removal credits

Installations can receive up to 2.0 log removal credit from cartridge filters and a 1.0 log removal credit from bag filtration.

The above log credits can be achieved if the following is achieved as a minimum:

- The cartridge and/or housing has been approved by a formally recognised standard [i.e. National Science Foundation (NSF), American National Standards Institute (ANSI)] to achieve a removal efficiency of at least 3 log for *Cryptosporidium*.
- The testing related to this certificate has been completed by an accredited inspection body and all testing was completed on the entire unit (housing, filter media, seals and all other relevant components).
- The equipment must be installed as per the layout used to complete the validation testing.
- Individual cartridge filters and housing are labelled as per the requirements of the NSF/ANSI 53–2002.
- Differential pressure (head loss) is measured across a filter housing that contains multiple filter elements. The minimum head loss across the unit must always exceed that of a clean filter as established during commissioning. It must also be kept within the manufacturer's recommendations.
- Turbidity (or particle counts of 2–5 μm) must be measured continuously from each housing.
- The feed water turbidity (or particle counts) must be monitored at the same frequency as the filtered water is monitored.
- The differential pressure (head loss) across each housing must be continuously measured.
- The flow to each individual housing must be measured continuously.
- The differential pressure must be measured immediately after cartridge replacement.

The following turbidity targets must be achieved:

- Turbidity must not exceed 0.5 NTU for more than 15 consecutive readings.
- Turbidity must not exceed 1.0 NTU for more than three consecutive readings.
- Filtered water turbidity must not exceed that of the feed water for more than three consecutive readings.

7.5.2 Regular operational checks

With the exception of the requirement for filter element replacement, there is very little requirement for operational activities to support the bag or cartridge filtration process.

Routine maintenance will be required for certain elements. The recommendations and maintenance instructions of the technology provider should be followed in this regard. Examples of critical maintenance tasks may include:

- pump maintenance;
- proactive replacement of filter housing O-ring;
- calibration of associated water quality instrumentation.

7.5.3 Operational records

In addition to the monitoring data available from online instrumentation, it is important that all operational logs and recorded information capture the following information:

- the serial numbers of each filter element installed in each housing, with position within the housing and date of installation, effective pore size, material details and terminal pressure for all installed cartridges;
- records relating to any events or occurrences that had an impact on the expected working life of the filter element(s).

7.6 Upstream and Downstream Considerations

7.6.1 Process inputs

There are no inputs required to support bag or cartridge filtration, other than the requirement to ensure that a minimum feed pressure is maintained.

7.6.2 Process residuals

Typically no process residuals are produced by the system. Some housings may require a small volume draining to waste.

Newer installations in the United States allow for a short duration run to waste. These have yet to be implemented in Ireland based on current knowledge. In these instances, it is expected that the small volume produced will be returned to the inlet of the DWTP or disposed of within the existing process residual treatment.

7.6.3 Upstream considerations

Cartridge filters are very dependent on upstream water quality. Any negative changes to upstream water quality, such as algal blooms or increased turbidity, can have an impact on filter lifespan.

Where upstream treatment is provided, consideration must be given to any chemical dosing. Treatment plants with cartridge or bag filtration should be operated with the aim of minimising the need for frequent start-up and shutdown.

As outlined previously, controlling flow and minimising the need for process start-up and shutdown are two of the most important operational parameters. Plant operations with cartridge filtration and bag filtration should operate the available DWTP assets as much as possible, to minimise the need for frequent start-up and shutdown. This will also avoid long periods during which the filters are operated close to their maximum hydraulic capacity.

7.6.4 Downstream considerations

Consideration should be given to managing, as far as possible, any downstream flow fluctuations that could have an impact on the cartridge filter (i.e. downstream pumping or any flow fluctuations that could cause downstream pressure fluctuations).

7.7 Process Start-up and Shutdown

7.7.1 General guidance

Process start-up and shutdown is a simple process. Effort should be made to slowly ramp up the flow and ensure that the minimum pressure is maintained.

7.7.2 Long-term shutdown and start-up

A cartridge filter or bag filter should be drained down before any planned long-term shutdown of the process units. This is done to minimise the risk of biological growth occurring within the filter element.

If the filter element and housing are compatible, it is beneficial to soak the filter in 1–5 mg/l chlorine before returning to service. Care should also be taken to ensure that the age of the filter element does not exceed that of the manufacturer's recommendation.

On returning to service, the initial filtrate should run to waste as it will be higher in turbidity. This is the result of flushing of any accumulated solids that were concentrated within the filter element during shutdown.

7.8 Process Troubleshooting

A review of potential issues, areas of investigative action and potential corrective action has been provided for cartridge and bag filters in Table 7.2. These identified issues should not be considered exhaustive but should be used to develop local operational procedures.

Generally, issues will fall into three general areas:

1. feed water quality;
2. maintaining and not exceeding pressure and hydraulic limits;
3. with filter integrity.

Table 7.2: Malfunction: clogging, turbidity or flow issues with of cartridge and bag filters

Issues	Recommended investigative action	Potential corrective action
Rapid clogging of filters (all housing affected)	Plant shutdown recommended (if possible) to minimise irreversible clogging of filter elements Review upstream process and whether there are any upstream water quality issues (i.e. algal bloom, upstream process issues) that could be contributing to clogging Review inlet pressure flow trends to ensure that all are within the allowable tolerances for the plant	Upstream corrective action as required Reduce flow throughput to minimise the impact on filter elements Replace filter elements
Rapid clogging of filters (limited to single housing)	Review inlet and pressure and flow trends. Ensure that all are within allowable tolerances Review air release valve and confirm satisfactory operation Inspect filter housing. Consider internal inspection and whether there is evidence of damage to a specific element or array of elements	Adjust flow and/or pressure to within tolerances of units Repair to air release valves or any other identified equipment Replacement of filter elements as required
Filtered turbidity exceed feed water turbidity	Issue is most likely attributed to a malfunctioning filter element(s) within a housing Review flow and pressure trends and ensure that there have been no irregularities that could have led to pressure shock Inspect filter housing and elements Confirm air relief valves are operating satisfactorily Confirm accuracy of turbidity instruments	Replacement of filter elements as required Corrective action to resolve identified pressure and/or flow irregularities Instrument calibration and or repair as required
Flow irregularity through filter housing	Confirm flow distribution between multiple housing. Confirm any valves and/or manifolds used for flow distribution Review inlet and outlet pressure trends to confirm there has been no incidents of pressure shock Review if any internal short-circuiting within the unit	Corrective action as required (i.e. valve repair) to restore even flow distribution Replacement of filter elements as required

7.9 Advantages and Limitations

Advantages are as follows:

- very low maintenance requirements (manual intervention required only to replace filter elements);
- minimal training requirements;
- lower capital cost (for small sites) and minimal footprint required for installation;
- no process residuals produced;
- no backwash requirements;

Limitations are as follows:

- single-use filter element which cannot be regenerated;
- technology may not be cost-viable for larger DWTPs;
- may not be cost-viable for source (or upstream) water with higher particle loads;
- additional pumping may be required to achieve the required feed pressure;
- filter elements can clog prematurely as a result of biofilm growth or coagulant residual.

8. MEMBRANE FILTRATION

8.1 Process overview

Membrane filtration is defined as follows (US EPA, 2005):

> A pressure or vacuum driven separation process in which particulate matter larger than 1 µm is rejected by an engineered barrier primarily through a size exclusion mechanism.

The types of membrane filtration are as follows:

- **Microfiltration (MF)** and **ultrafiltration (UF)**: low-pressure membrane filtration processes that are used primarily to remove particulate matter and microbial matter, using a size exclusion (i.e. sieving) mechanism across a porous membrane (refer to section 2.1). An example of an ultrafiltration plant is show in figure 8.1.

Figure 8.1: Example of an ultrafiltration plant.

(Image provided by Pentair)

- **Nanofiltration (NF) and reverse osmosis (RO)**: semi-permeable, high-pressure membrane separation processes that remove particulate matter using a size exclusion mechanism, but also remove dissolved contaminants. Dissolved contaminants are removed using the filtration mechanism of RO (refer to section 2.1). NF and RO work identically; however, NF membranes are more permeable than RO membranes. NF will therefore have a lower removal efficiency and operates at a lower operating pressure than RO. Neither RO nor NF membranes have defined pores as outlined in section 2.1.

Membranes are classified by their pore size and/or molecular weight cut-off (MWCO), which are defined as follows:

- **Pore size**: the diameter of micropores in a membrane material. Nominal pore size represents the average pore size, whereas absolute pore size reflects the maximum pore size.
- **Molecular Weight Cut Off (MWCO)**: molecular mass of a solute for which a membrane achieves > 90% removal.

Table 8.1: Indicative classification of membranes[4]

Type	Pore size (μm)	Molecular Weight Cut Off (daltons)	Typical operating pressure (bar)
Microfiltration	0.1–0.5	> 200,000	1–2.5
Ultrafiltration	0.01–0.1	10,000500,000	1–2.5
Nanofiltration	0.001 (notional value)	200–1000	6–14
Reverse Osmosis	0.0001 (notional value)	< 100	7–80

The general process overview is as follows:

- **Forward filtration**: the membrane filter units are in service and produce filtrate.
- **Backwash**: a membrane unit is taken offline to backwash, which removes particles and solids that have accumulated on the membrane surface. Some installations will use a chemical-enhanced backwash (CEB), which involves dosing a chemical to the backwash feed water.
- **Direct integrity testing**: a manufacturer-specified procedure that identifies and isolates any membrane modules that have suffered an integrity breach. The membrane unit is taken offline to complete the test. The test will determine if the membrane is free of any defects or leaks that could allow inadequately filtered water to bypass the membrane barrier. Generally, there are two types of integrity tests: pressure-based tests and marker-based tests which are differentiated as follows:
  - Pressure-based tests involve applying a pressure or vacuum and monitoring for pressure loss, or the displacement of air and water, to ascertain if an integrity breach is present.
  - Marker-based tests use a spike particulate, or a molecular marker, directly measuring the removal of the marker across the membrane.
- **Membrane cleaning**: chemicals are required to remove foulants that accumulate on the membrane surface and cannot be removed by backwashing. The unit is taken offline and is soaked in a chemical solution for a defined period of time to restore permeability of the membrane. The typical chemicals used are outlined in section 8.3.2.
- **Membrane replacement**: despite regular chemical cleaning and backwash, the membrane material will experience irreversible fouling over its working life. Most applications will have an expected working life of 5–7 years.

4 The table was derived from various sources: US EPA (2001), US EPA (2005) and New Zealand (2017) and Twort (2016).

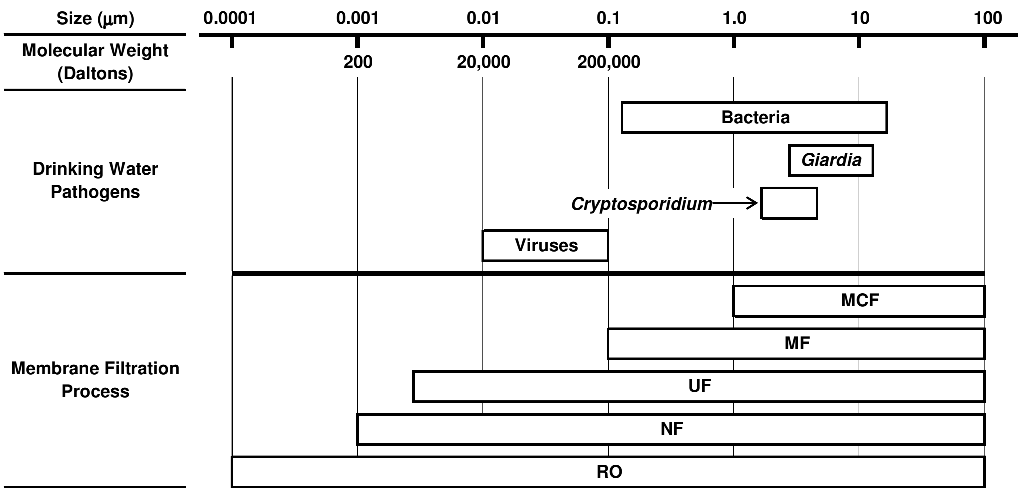
8.1.1 Filtration objectives

Membrane technologies are generally used for the following:

- **Pathogen barrier**: membranes offer an effective barrier against pathogens. UF/NF and RO will remove viruses, bacteria and protozoa. MF will remove protozoa and most bacteria but should be followed with a full chemical inactivation process downstream.
- **Targeted removal**: NF and RO semi-permeable barriers are effective at removing some dissolved compounds, including soluble metals and organics, and hardness.

Figure 8.2 provides a guide to the membrane filtration processes suitable for removal of different drinking water pathogens.

Figure 8.2: Filtration application guide for pathogen removal.[5]



The abbreviation MCF in Figure 8.2 refers to membrane cartridge filter. This term is used within the US EPA Regulatory Framework to apply to cartridge filters that meet the definition of membrane filtration, can reliably remove all particles larger than 1 µm and can be subjected to direct integrity test. There are no known applications of this type of cartridge filtration in Ireland; however, should it be implemented, the guidance both in this chapter and in Chapter 7 should be considered.

8.1.2 Membrane challenge testing

As outlined in the US EPA *Membrane Guidance Manual* (US EPA, 2005), there are no specific design criteria that can be applied to membranes and guarantee the removal efficiency of membrane processes. Challenge testing is completed directly by the manufacturer and a validated third party. It quantifies the removal efficiency of a specific membrane technology. Once validated, a membrane product does not need to be re-tested at every site of installation.

5 (US EPA, 2005).

8.2 Process Equipment and Layout

Membrane technologies are modular systems that are sourced directly from the equipment supplier. Key components include:

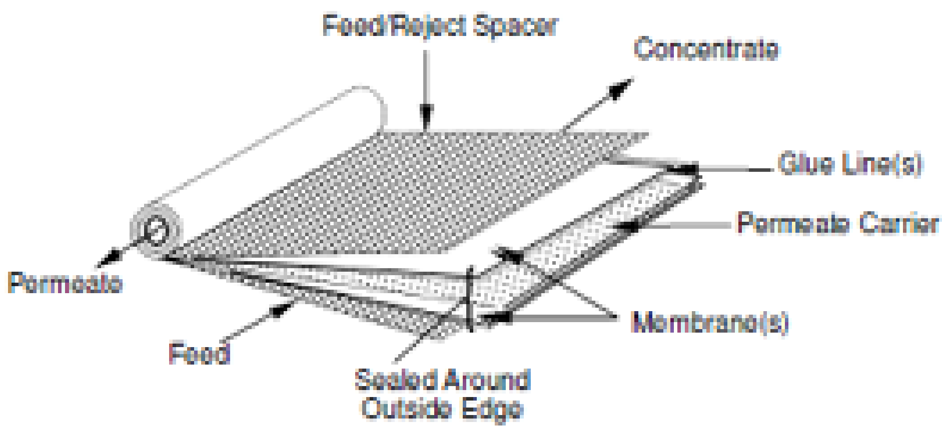
1. **Membrane material**: UF and MF membranes are typically manufactured from a synthetic polymer, including polyvinylidene fluoride (PVDF), polypropylene (PP) and cellulose acetate (CA). Ceramic membranes, which are gaining popularity, are discussed in Chapter 10. UF and RO membranes are typically manufactured from polyamide (PA) materials or CA materials.
2. **Membrane module**: this is the smallest discrete filtration unit in a membrane system. The two main configurations found in drinking water applications, hollow-fibre and spiral wound, are described below. Additional configurations exist, including tubular, hollow-fine fibre and plate and frame, but these are not discussed because their use in drinking water is limited and they are unlikely to be installed in Ireland.
   - **Hollow-fibre**: membrane module containing numerous long and narrow tubes. This configuration is typical of most MF and UF installations. A single module can contain several hundreds to over 10,000 of the hollow fibres. The fibres can be 1–2 m in length, with an approximate inner diameter of 0.3–1.0 mm. The membranes are most commonly mounted vertically, but horizontal configurations are also used. The membranes can operate “inside-out” or “outside-in”. An example of a hollow fibre module is show in Figure 8.3.

Figure 8.3: Example of hollow-fibre module.

(Image provided by Pentair)

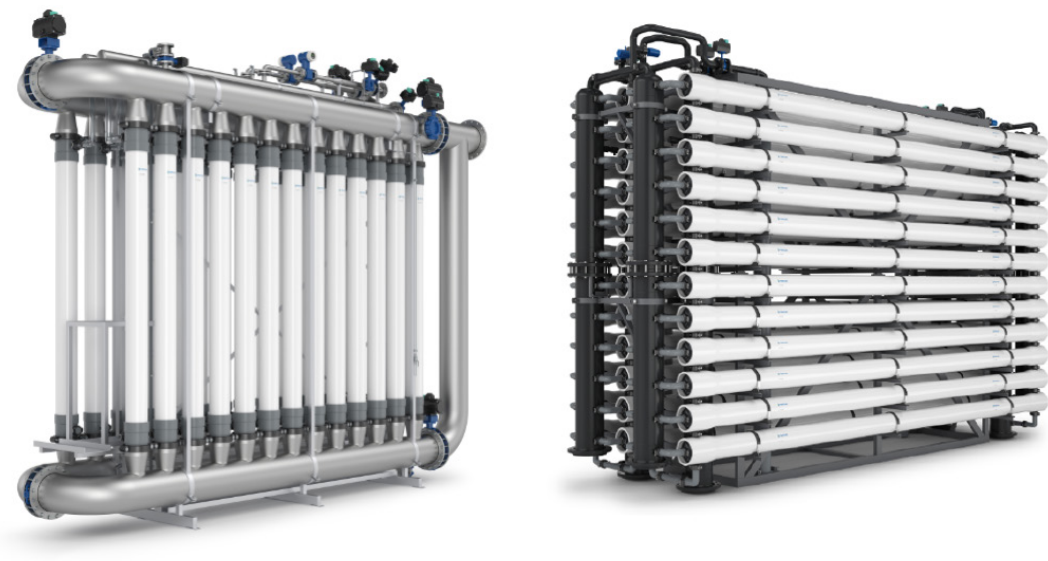
Spiral wound: a flat sheet of membrane material that is wound around a central perforated tube. Two membrane sheets are separated by a small fabric sheet, which acts as a permeate carrier called a “leaf”. One edge of the leaf is sealed around the central tube, while the remainder are glued together. Each leaf is then separated by a structured plastic mesh that provides an inlet for feed water. A 20-cm-diameter module could contain over 20 of these leaves. The configuration is shown in Figure 8.4. Typical sizes are 10–20 cm in diameter, with a length of 1–1.5 m. This configuration is typical of most NF and RO installations.

Figure 8.4: Configuration of spiral-wound membrane.[6]



3. **Membrane unit**: a group of modules with shared common valving, also referred to as a skid. The unit can be isolated from the rest of the system for integrity testing or other maintenance. Membrane units are configured as:
   - **Pressurised system (Figure 8.5)**: membrane modules are contained within a pressure vessel, which provides the driving force across the membrane.
   - **Submerged (Figure 8.6)**: modules are completely submerged in a feed water tank. A vacuum is applied to the treated water (permeate) side to force water across the membrane material.

Figure 8.5. Example of pressurised horizontal and vertical configurations.



(Images provided by Pentair)

6 (US EPA, 2005).

Figure 8.6: Example of submerged membrane.

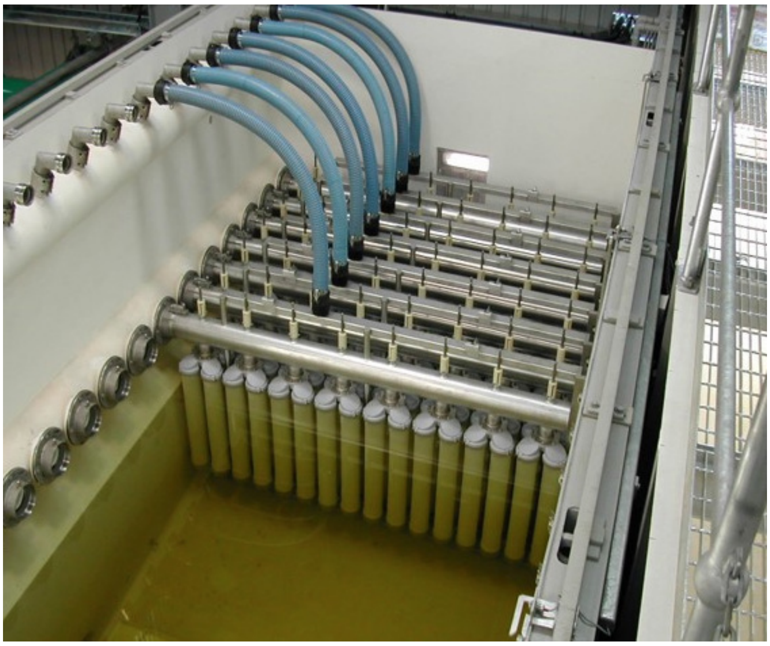
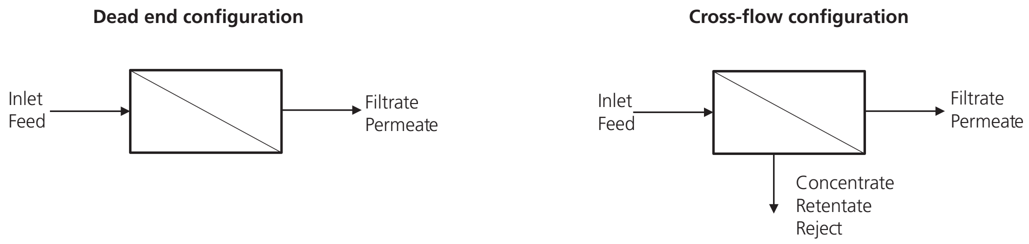


Image provided by Evoqua Water Technologies

4. **Filtration driving force**: membranes will be either pressure or vacuum driven, defined as follows:
   - **Pressure driven**: most applications require a feed pump to provide the required driving force; however, some UF/MF facilities may be able to achieve the required driving force with gravity flow to the membrane units.
   - **Vacuum driven**: most applications require pump suction to provide the required driving force. Some facilities may be able to implement a gravity flow siphon to achieve the required driving force.
5. **Hydraulic configuration (Figure 8.7)**: two hydraulic configurations are typically used with membrane filtration processes, as follows:
   - **Dead end**: all water entering the system leaves in the permeate stream. There is one inlet and one outlet. Accumulated particles will accumulate on the surface of the membrane, forming a cake layer. This layer is periodically removed by backwashing, back-pulsing and/or chemical cleaning. Some systems may apply a scouring force in which water and/or air is applied to minimise the accumulation of contaminants on the membrane surface;
   - **Cross-flow**: the system has an inlet, treated (permeate) outlet and a concentrate stream. The influent flows parallel to the membrane surface and most of the water passes through the membrane into the permeate stream. Any remaining water will leave the unit in the concentrate stream. The velocity of the water should be high enough to provide a scour on the membrane surface, meaning particle deposition is minimised.

Figure 8.7: Hydraulic configuration of membranes.



- **Submerged tank**: the membranes are completely submerged in a large open tank and typically operate as follows:
  - Plug flow: applies to submerged membrane systems. The feed water concentration will vary across the length of the tank housing the membranes, maximising at the end of the tank (where the filtrate is collected).
  - Continuous stirred tank reactor (CSTR): the feed water is continuously mixed, meaning each membrane module is exposed to an equivalent feed water concentration.

6. **Additional stages of membrane units**: to improve plant recovery (the percentage of feed water flow that is converted into filtrate flow), many installations will have a secondary treatment unit to provide additional filtration for either backwash waste water or the concentrate stream (from cross-flow configurations). Additional stages will typically be smaller, as the inlet volume will be reduced compared with the feed fed to the first stages.
   - For NF and RO systems the percentage recovery depends on the incoming total dissolved solids (TDS) in the water. For very saline water, poor recovery of 15–30% may be experienced (TDS > 50,000 mg/l). Brackish water applications (TDS > 5000 mg/l) can have up to 75% recovery. Treating the concentrate from the first unit in a second stage can improve this to up to 75%, while adding a third stage can achieve recoveries of > 90%. Note that, for RO/NF applications, TDS will typically be measured using conductivity as a surrogate.

8.3 Design Considerations

8.3.1 General concepts membrane systems

Some terms critical to understanding the key design concepts for membrane filtration are defined below:

- **Unit recovery**: the amount of feed flow that is converted into filtrate flow.
- **Transmembrane pressure (TMP)**: the pressure gradient across the membrane, i.e. the pressure on the feed side of the membrane minus the filtrate pressure. Where a cross-flow arrangement is in place, the TMP is given by the average of the feed and concentrate pressures minus the filtrate pressure (MF and UF only).
- **Net driving pressure (NDP)**: applies to NF and RO applications. NDP is the pressure available to force water through the membrane. It is computed by taking the average pressure on the feed–concentrate side of the membrane minus the permeate backpressure and minus the differential osmotic pressure across the membrane. This is considered equivalent to TMP for the rest of this chapter.

- **Resistance**: resistance to flow acting in opposition to the driving force, inhibiting the transport of water across the membrane, can also be quantified. The resistance will be the sum of the resistance of the membrane material and any resistance resulting from accumulated fouling during the operation service of the membrane.
- **Membrane flux**: the filtrate flow per unit of membrane filtration area (l/h/m^2 or LMH). The flux is a function of the TMP, total resistance and water viscosity (temperature dependent). As water temperature decreases, larger TMP is required to maintain a constant flux, given that viscosity increases as temperature decreases. For this reason, the flux that is captured and trended at a DWTP is often normalised to 20 °C (UF/MF) and 25 °C (RO/NF) to allow for comparison between data. This is because the data will identify any changes in flux that are due to TMP changes, probably attributable to fouling. Sometimes the flux is also normalised for pressure, which allows a more direct identification.
- **Silt density index (SDI)**: generally considered for RO/NF applications, it is an on-site measurement of the suspended solids concentration in the feed water to the membranes. Significant levels of very fine particles perhaps (i.e. silt) in water can result in frequent membrane cleanings, or even premature membrane failure. Frequently, particles causing potential membrane fouling average < 5 µm in diameter and the water may appear clear.

8.3.2 Design considerations for membranes

Hollow-fibre membrane systems are typically proprietary systems, meaning that the entire filtration system is supplied directly from the membrane technology provider. Components are not interchangeable between different technology providers.

The membrane supplier will typically specify the following:

- hydraulic configurations;
- material of construction;
- backwash and chemical cleaning requirements;
- integrity testing;
- control system;
- supporting mechanical and electrical equipment, including blowers and automatic control valves.

In contrast, spiral-wound membrane systems are not fully proprietary. Standard-sized membranes are typically interchangeable between membrane plants.

The following design parameters are often considered in consultation with the membrane technology provider:

- **Flux**: the critical operating flux is a very important parameter. It is directly correlated with the lifespan of a membrane module, which is a significant portion of the total capital cost of a membrane filtration plant. A well-designed system will maximise the flux without causing excessive irreversible fouling, which is often referred to as the "critical flux" point. The higher operating flux will also increase the required frequencies for backwash, and chemical cleans, while operating at a lower flux, will produce water that is less treated. The determination of the "critical flux" is application-specific and depends on numerous factors, including feed water quality, pore structure, water temperature, and physical properties of the membrane material and structure.

Membrane systems typically operate at constant pressure, meaning that the flux and filtered water output will decrease as fouling increases. Alternatively, some sites will operate under a constant flux and increase the pressure (or vacuum) driving force to account for fouling and ensure that consistent filtered water output is maintained.

- **Backwash**: only hollow-fibre membranes can be backwashed. The backwash process is similar to that of media filtration and should be seen as the first line of the defence for managing membrane fouling. During a backwash event, the flow is typically reversed for a period of 30 seconds to several minutes. The frequency of backwash is much greater, often every 15–60 minutes. It is not uncommon for 5–10% of the membrane filtrate to be lost to backwashing requirements. Some systems will use air in combination with water for the backwash. Some systems will also use a CEB, in which a chemical is injected (e.g. chlorine or sodium hydroxide).
- **Chemical cleaning**: typically referred to as clean-in-place (CIP), the chemical clean is the second line of defence for managing fouling on the membrane. The required cleaning procedure is generally provided by the membrane supplier. It targets inorganic, organic and biofouling that cannot be dislodged by backwashing alone and depends on the types of foulant(s) present in the source water. For NF/RO applications, chemical clean is the only control in place to mitigate against fouling. Sometimes, the chemical solution will be heated to further enhance the removal of the target contaminant(s). This increases general solubility. The typical chemicals used are given in Table 8.2.

The general CIP sequence is as follows:

1. The cleaning chemical is recirculated through the membrane system at high velocities to generate a scouring action.
2. The chemical is soaked for a period that can be of short duration (15 minutes) or up to several hours (soak cycle).
3. All residual cleaning chemical(s) is flushed out of the system (flush cycle).
4. Occasionally, the process is repeated with a second chemical (e.g. a caustic wash targeting organic fouling, followed by acid wash targeting accumulated fouling, due to metals present in the source water). Caustic is generally used prior to acid wash.

Softened (demineralised) water may be required to avoid scaling on the membrane and/or avoid issues with scaling in the waste chemical pipework and is used to make up the chemical solution(s) used for the CIP.

Table 8.2: Chemicals typically used for membrane chemical cleaning

Type	Common chemicals	Targeted contaminants
Acid	Citric acid ($C_6H_8O_7$) Hydrochloric acid (HCl)	Inorganic scaling
Base	Sodium hydroxide (NaOH)*	Organic compounds Biofoulants
Oxidants	Sodium hypochlorite (NaOCl) Hydrogen peroxide (H_2O_2)	Organic compounds Biofilms
Surfactants	Various	Organics General particulates
Proprietary	Various	Various

*NaOH is sometimes combined with sodium hypochlorite for a single chemical wash.

- **Downstream chemical conditioning**: RO/NF applications have an impact on the general water chemistry as they also remove dissolved compounds. These applications often include upstream pH adjustments to lower pH, which increases the solubility of organic compounds. As a result, any carbonate and bicarbonate alkalinity is converted into carbon dioxide (CO_2), which can pass through the membrane structure. The filtrate is often corrosive as a result of this elevated CO_2 concentration and low pH. Chemical conditioning is completed to stabilise the filtrate and increase its alkalinity (buffering capacity) and pH and to stabilise dissolved gases. Typically, this can include one or a combination of the following:
  - addition of alkali chemical (lime or caustic);
  - addition of alkalinity (sodium bicarbonate);
  - air stripping.
- **Upstream water quality**: any high solids loading will lead to more rapid clogging of the filter pores. Consideration should be given to any risk of biofilm growth within the media. Sodium hypochlorite (once material compatibility is confirmed) can be added upstream of the filter to control any risk of biological growth. The presence of organic carbon can cause membrane fouling. Water temperature also has an impact as output (flux) will decrease with decreasing water temperature or require increased operating pressure to maintain a consistent flux. Seasonal temperature is a critical parameter to ensure that a facility can maintain its maximum output during cold weather.

  RO/NF systems will require defined pre-treatment, often including clarification and/or filtration with chemical dosing. Depending on the application MF/UF, systems may have only basic pre-filtration to remove coarser solids.
- **Pre-filtration**: a pre-filtration technology can be selected to ensure that all particles above a certain size (application specific) are removed to avoid premature fouling of the membranes.
- **Upstream chemical conditioning**: chemical conditioning is nearly always required for NF/RO applications. As a minimum the following should be considered:
  - Scale inhibitor: consider adjustment of pH and/or addition of antiscalant chemical.

- pH adjustment: some membrane materials are sensitive to pH and operating pH must be kept within a strict range (e.g. cellulose acetate requires pH 4–8).
- Chemical disinfectant: some applications may dose chlorine upstream of membranes to control biofouling on membrane surface. Many membrane types are damaged by strong concentration of oxidations, including chorine, requiring residuals to be quenched upstream of the membrane.
- Chemical coagulant: the use of coagulant upstream of some applications can reduce fouling and improve removal of targeted compounds (i.e. dissolved organic carbon).

- **Process redundancy**: the design must ensure that there is sufficient filter capacity (number of filters and available surface area of filtration media) that the maximum allowable flux is not exceeded during times of worst-case water quality or low temperature or when units are offline for chemical cleans.
- **Continuous operation**: membrane filtration plants should be run continuously as much as possible. Frequent start-up and shutdown can lead to hydraulic and pressure surges, which can contribute to operational fatigue in the long term. In the case of small systems, consideration should be given to downstream water storage to allow constant operation where possible, or planned periods of offline (i.e. during peak energy tariffs).
- **Cross-connection control**: a control for ensuring that any chemicals from the chemical clean do not contaminate the feed or filtrate streams must be in place. This is commonly accomplished with a block and bleed valve arrangement, in which a "bleed" valve, located just upstream of the inlet valve on the common inlet manifold, can be opened. This bleeds any cleaning wastes that leak through the inlet valve directly to waste.
- **Consideration for run to waste:** a run to waste may be required following chemical cleans. This will divert any of the initial filtered water that does not achieve the water quality objectives for the plant (typically turbidity and/or pH) as a result of residual chemical remaining in the membrane system.
- **Residuals treatment**: because of the chemical cleaning required, it is common that generated wastes require some treatment. This can include neutralisation of any acid and/or alkali wastes and quenching of residual chlorine.

Some cartridge filter applications contain a defined membrane filtration medium that is fixed to a disposable cartridge element. If this type of cartridge achieves the required particle size removal and can be tested with direct integrity testing, it can be considered a membrane filtration process. This technology is not widely used in Ireland, currently. However, if implemented, the guidance in this chapter should be considered with respect to direct integrity testing and consideration of additional critical control parameters not identified in Chapter 7on cartridge filtration.

8.3.3 Consideration for pilot studies

Pilot trials are sometimes recommended when assessing a full-scale design of a membrane system. They should be completed when there are potential knowledge gaps with respect to raw water quality. Pilots trials are completed to determine and optimise the following:

- potential operating flux;
- backwash and chemical clean frequencies;
- chemical selection for chemical cleans;

- expected energy costs;
- upstream chemical addition (i.e. antiscalants, pH adjustment and coagulants);
- downstream chemical condition requirements.

There are numerous modelling software packages available to designers to help select the most suitable membranes based on water quality. This is typically done by the membrane supplier.

8.4 Guidance on Operation

Membrane plants are typically fully automated and require minimal operator attention, other than confirming key operating parameters. Operational teams must take care when adjusting plant set points to ensure that all relevant data trends and critical control parameters (as outlined in section 8.5) are carefully and regularly reviewed. Careful attention needs to be given to TMP trends and confirmation that the rate of irreversible fouling is not increasing.

Specialist knowledge is required to complete the process reviews necessary at membrane treatment plants. Many plants, particularly smaller systems, engage a third-party specialist (typically membrane technology provider or membrane chemical supplier) to review process performance and carry out regular site visits to approve operational practice. However, plant operators need to receive the training and specialist knowledge required to maintain, troubleshoot and optimise the membrane plant.

8.4.1 Forward filtration

Operational staff should focus on ensuring that all membrane units are maintained in supply and long-term shutdowns are avoided. Where chemical cleaning is completed by manual initiation, the clean cycle should be staggered across the different membrane skids to minimise the impact and avoid potential seasonal challenge periods (i.e. cold weather, which can reduce plant production, or seasonal water quality challenges).

Membranes are robust when cared for adequately. However, they prefer continuous operation, and care should be taken to avoid long-term shutdown of these processes (see section 8.7.3). Frequent start-ups and shutdowns can also damage membrane integrity over time.

8.4.2 Backwash

Backwash frequency is typically completed in line with the manufacturer's recommendations. Typically, backwash is triggered by operational time, but it can also be configured for decreases in volumetric throughput, increase in TMP and/or a decline in flux.

8.4.3 Clean-in-place chemical clean

The objective of chemical cleaning is to restore the TMP of the membrane modules to their baseline or clean level. Any foulant that is removed by backwash or chemical clean is considered to cause reversible fouling.

For systems where backwash is completed, the CIP can be triggered when the backwash is no longer effective at reducing TMP back to the desired baseline value. For NF and RO systems, a 10–15% decline in the normalised flux, or a 50% increase in differential pressure, is a good trigger for backwash. Many facilities will complete CIPs at regular time intervals to minimise any risk, especially where there is no regular review of trended data to confirm that baseline TMP is being achieved.

While it is inevitable that irreversible fouling slowly accumulates over the working life of the membrane, failure to carry out CIP can lead to premature irreversible fouling, which will shorten membrane life and the production capacity of the membranes. MF/UF systems will typically require a CIP every few days to once per month, although high-quality feed waters will allow for longer operation. NF/RO systems typically require less cleaning and may require a CIP sequence only every 3–12 months.

Some manufacturers may recommend a shorter duration chemical clean on a pre-set interval to minimise the risk of accumulation of foulants. The objective of a shorter duration chemical clean is similar to that of a chemical enhanced backwash and is completed, typically, from several times a day to several times a week.

It is important to ensure that the membrane unit is adequately flushed to remove any chemical before forward filtration is resumed. Some systems may operate a run to waste to divert any filtrate to waste, until suitable water quality is achieved (i.e. as determined by monitoring turbidity and/or pH for MF/UF systems, pH for RO/NF systems).

MF/UF systems will often recycle up to 90% of the chemicals used for the cleaning sequence. This practice is less common in NF/RO systems since the cleaning solution will accumulate dissolved compounds removed during the cleaning, which will have an impact on the efficacy of the cleaning chemical(s). Regular operational checks are required to confirm that adequate chemical concentration is achieved (i.e. by ensuring that target pH, residual chlorine level or temperature is achieved).

Operators of membrane plants should ensure that TMP trends are regularly reviewed to confirm the effectiveness of the CIP sequence.

8.4.4 Direct integrity testing

Membranes are monitored by both direct and indirect integrity testing. The fundamental difference between these test types is set out in section 3.2. In membrane plants the direct integrity test is required to be undertaken in accordance with procedures as specified by the manufacturer for the purposes of identifying and isolating any membrane modules that have suffered an integrity breach

The direct integrity test is generally an automated process that is completed on a specific membrane skid. If the test indicates an adverse result, the unit is immediately removed from service and on-site investigations are required. The on-site investigations can often be operationally intensive. Each unit contains many modules. Often the integrity test is completed by isolating different modules to identify if the issue is across the unit or specific to certain module(s).

There are many potential issues that could lead to an issue with the integrity of the membrane. These include:

- damage to membrane material due to exposure to chemical oxidations, pH outside operating range, exposure to incompatible chemical;
- breakage due to exposure to high pressure;
- physical damage to the membrane due to abrasions or operational fatigue;
- factory imperfections;

- failure of O-rings or other interconnections;
- working life of membrane has been exhausted.

When the membrane is used as a barrier to pathogens, daily integrity testing should be completed. An integrity test should also be completed on any membrane unit that has been removed from supply for maintenance, before it is re-entered into the treatment train.

8.4.5 Membrane pinning

Specific to hollow-fibre membranes, many facilities will have on-site repair capabilities. Damage to a single hollow fibre can be removed by a procedure referred to as "pinning", in which the two ends of a hollow-fibre membrane are blocked to prevent any further inlet flows. This can be a very time-consuming process that requires specialist training. The general process is as follows:

- The modules that need to be repaired are removed from the membrane skid.
- The modules are placed in a water bath with the ends fully submerged in water. A source of air is directed upwards through the module;
- Air bubbles will appear from the membrane "straws" that have an integrity issue. The end of a broken straw is pinned (capped off to isolate it from any inlet flows). The pin is typically metal or plastic. A pin must be inserted at both ends of the membrane. It is not uncommon to have to repair several straws simultaneously.
- The unit is replaced, and the direct integrity test repeated to ensure that integrity has been restored.

Pinning is likely to be a regular occurrence in hollow-fibre plants, and the frequency of pinning will increase as plant age increases. Increasingly frequent pinning or the presence of multiple modules with multiple pins may indicate that the membrane condition is starting to degrade and should trigger planning for a module replacement. Once a module has in the range of 5–10 pins it should be replaced.

8.4.6 Replacement of membrane module

It is expected that some membrane modules will require replacement before the expected working life of 5–7 years has expired. Membrane modules are typically shipped in a sealed bag to maintain integrity. The bags often contain a small volume of disinfectant (such as sodium bisulphite), glycerine or a proprietary solution.

Each type of membrane manufacturer will have specific guidance for the installation of new membrane modules. Each DWTP should maintain a procedure that details the activities required for the particular technology in place. Failure to complete the recommended installation tasks could shorten the life of the membrane module. Examples of typical tasks include any one or combination of the following:

- extended soak in hypochlorite to maximise membrane porosity;
- flushing of storage fluid, which can include a combination of backwash and forward flushing to waste;
- chemical clean;
- air integrity test.

8.4.7 Manufacturer's warranty

Membrane modules are typically subjected to a performance guarantee or warranty on the working life of a membrane. Facilities must take care to operate the facility and ensure that there is sufficient data capture and operational records maintained to verify that critical activities have been completed. The manufacturer's warranty typically specifies the following:

- upstream water quality tolerances;
- requirements for chemical cleaning, including minimum frequencies;
- critical operational activities;
- storage requirements for stored membranes.

8.4.8 Process optimisation

The following can be considered for process optimisation:

- **Energy management**: membranes are an energy-intensive process. The brine produced from RO desalination applications has a very high pressure and can be used for energy recovery. Efficient energy recovery systems can reduce the energy consumption by approximately 50%.
- **Chemical cleaning frequency**: basic manufacturer's recommendations are often conservative and DWTP facilities can often further optimise the process. However, it is imperative that the chemical cleaning frequency does not decrease below the minimum requirements to maintain module warranties. Regular process reviews should be completed to confirm the effectiveness of the chemical cleans. No optimisation of the chemical cleaning frequency should be completed where sufficient process reviews have not been completed. These reviews ensure that a reduced cleaning frequency is not having a negative impact on the TMP profiles, in particular the occurrence of irreversible fouling (which can be slow to build up).
- **Membrane autopsy**: it is often difficult to predict what the effective working life of a membrane module will be. Most applications typically last 5–7 years. It can be beneficial to send a used module for an autopsy by the technology provider. This can provide insight into the module's degradation but can also be effective in troubleshooting any issues that lead to premature failure of membrane modules (i.e. accumulated solids in membrane pores, evidence of brittleness).
- **TMP profile**: the TMP of each membrane unit should be regularly recorded and trended. This can be useful to monitor trends in TMP from the date of installation of the membranes and for comparison with projections on the rate of increase in TMP over time owing to irreversible fouling. This can be beneficial in highlighting any potential issues at the plant that have changed the rate of fouling and could shorten the life of the membranes.

8.4.9 Critical spares

It is important to have critical spares on-site or readily accessible to allow for replacement of any membranes that fail prematurely. At least 10% of the required membrane modules should be stored on-site as critical spares. The modules must be stored in line with manufacturer's recommendations.

As the typical membrane module lifespan is 5–7 years, membranes will be replaced several times over the life of the plant. As membrane companies develop new products, it is often the case that the modules required at older installations cannot be purchased off the shelf from the manufacturer. The production must be scheduled directly with the manufacturer's factory production line, which can take several months to arrange.

Many manufacturers will also guarantee a store of critical spares, guaranteeing access to a defined number of spare modules with an agreed time-frame.

8.5 Critical Control Parameters

The identification of critical control parameters is an important aspect of applying the DWSP methodology. Table 8.3 summarises the recommended critical control parameters and associated control measures for membranes.

Table 8.3: Critical control parameters for membrane filtration

Critical control parameter	Significance	Recommended control
Feed water turbidity	It is important to measure the feed water turbidity at the same frequency as the filtered water turbidity to confirm that there is no issue within the membrane units An alarm should be configured if filtered turbidity exceeds feed water turbidity for at least 3–5 minutes Some sites may have a risk of elevated turbidity in the feed water due to upstream treatment issues and/or source water challenge events. It may be appropriate to trigger a site shutdown if the feed water turbidity exceeds the allowable threshold	Continuous online turbidity instrument Turbidity alarm
Combined filtrate turbidity (and/or particle counting)	This should be provided when pathogen removal is a target from the installed filtration processes Outlet monitoring will allow for identification of an individual housing that might have an integrity issue Turbidity from membrane processes should be < 0.1 NTU at all times. Turbidity will often identify only serious upstream issues. Particle-counting instruments are sometimes used instead of, or in conjunction with, turbidity to verify filtrate quality	Continuous online instrumentation High-turbidity alarm Process shutdown
Flow rate	Flow rate should be measured on each individual membrane skid to confirm balanced flow. Flow is also useful to identify where membrane permeability has decreased, impacting on membrane recovery and reducing treated water yield	Continuous online instrumentation
Recovery (%)	The percentage recovery is a valuable metric to monitor the effectiveness of the membrane process	Continuous monitoring via SCADA (supervisory control and data acquisition) system

Critical control parameter	Significance	Recommended control
TMP	The TMP should be normalised for temperature and pressure. TMP is calculated by the membrane control system and can be used to: trigger backwash trigger chemical clean confirm when membrane replacement is required TMP is measured across a common membrane unit (or skid)	Alarm and process unit shutdown if TMP is excessive Automatic trigger for backwash and CIP Alarm for failure of chemical clean
Temperature	Temperature can also have an impact on membrane flux. Understanding of the design operational range of the membranes is critical, although given the nature of the climate in Ireland this may not be a significant issue The temperature of the filtrate is used to configure normalised TMP Some installations will also require temperature measurement to confirm that a chemical clean is completed at the required temperature	Continuous online instrument Operational procedure Alarm for failure of chemical clean
pH and/or conductivity	These parameters are used to verify upstream and/or downstream conditioning, and also used to verify that the backwash and/or chemical clean chemicals have been adequately flushed from the membrane units Where a concentrate stream (refer to Figure 8.7) is in place (i.e. for cross-flow systems) conductivity should be measured from each membrane skid.	Alarm Automated process unit shutdown Continuous on-line Instrument
Direct integrity testing	The direct integrity test method is specified by the manufacturer and must be completed at the recommended frequency. The test is completed on a membrane unit and an automatic shutdown should be configured in the event that the integrity test: does not complete; has an unsatisfactory result. When an integrity test indicates a potential issue with a membrane module within a unit, a documented procedure should be available to clearly identify which operational responses are required by which specific issues.	Operational procedure Automatic process unit shutdown
Salt rejection	For RO applications, measuring salt rejection (percentage of feed water TDS that have been removed in the permeate) is a direct means of monitoring performance For RO, TDS will typically be measured using conductivity as a surrogate	Continuous monitoring (and recording via SCADA) of conductivity (or TDS) in feed water and permeate

8.5.1 Guidance on log removal credits

The New Zealand *Guidelines for Drinking-Water Quality Management* (New Zealand Ministry of Health, 2017) allow for three or more log credits for membrane filtration. For a membrane technology to qualify, it must have a measurable removal efficiency of a target organism that can be verified using a direct integrity test.

MF, UF, NF and RO are all eligible for log credits if the following is achieved as a minimum:

- Direct integrity tests are performed on each membrane filter unit daily.
- The direct integrity test method used to verify membrane integrity must be capable of detecting a 3 μm hole in the membrane surface and must also be capable of verifying the log removal value claimed by the manufacturer.
- The turbidity of the filtrate from each unit and the raw water feed must be continuously monitored. Alternative continuous monitoring that is specified by the manufacturer (e.g. particle counting) must also be provided.
- Direct integrity testing is required if the membrane has been out of service for maintenance, or if turbidity from the membrane unit exceeds 0.1 NTU for more than 15 consecutive readings (the maximum allowable measuring frequency being every 1 minute).
- No membrane filter can be used that has failed its direct integrity test.
- Validation testing has had third-party accreditation.
- The manufacturer has certified the required performance specifications and operational and maintenance requirements to ensure that the module will perform to these specifications.
- Any direct integrity test results that exceed the manufacturer's recommendations must be investigated and appropriate corrective actions taken immediately. The results must be documented.

The log credits assigned to a particular membrane technology type are determined by the manufacturer's validation certification for the target organism(s). The certificate must document the challenge testing completed, typically by the method outlined in the US EPA Membrane Guidance (US EPA, 2005). The certificate must also outline any specific operational and maintenance requirements. The integrity testing procedure that the operational team at the water treatment plant must carry out must also be documented.

8.5.2 Regular operational checks

Routine maintenance will be required for certain elements, but the tasks required will be based on the operation and maintenance instructions provided by the technology provider. Examples of critical tasks may include:

- review of the chemical clean sequence to confirm that the target pH and/or temperature is achieved (as required);
- regular inspection and proactive replacement of membrane unit O-rings;
- calibration of associated water quality monitoring instrumentation;
- review of TMP trends to confirm suitability of cleaning frequency;
- review of pressure and flow trends to confirm that each membrane skid is receiving adequate and balanced flows
- any required on-site testing on feed, reject and filtered water.

8.5.3 Operational records

In addition to the monitoring data available from online instrumentation, it is recommended that all operational logs and recorded information include, as a minimum, the following:

- the serial numbers of each membrane module installed in each membrane unit, with position within the unit and date of purchase and date of installation;
- records of any pinning completed;
- records relating to any events or occurrences that had an impact on the expected working life of the membrane modules(s) (i.e. failure to complete chemical clean, any operational events that could contribute to operational fatigue, such as prolonged running at high flux);
- the dates of any chemical cleans.

8.6 Upstream and Downstream Considerations

8.6.1 Process inputs

The primary consideration is the requirement to ensure that a minimum feed pressure and inlet flow are maintained. Some applications may require upstream chemical conditioning including:

- pH adjustment;
- coagulation;
- chlorination and/or de-chlorination;
- addition of scale inhibitor chemical;
- addition of chemicals for chemical enhanced backwash and/or chemical cleans.

8.6.2 Process residuals

The following process residuals are typically produced, depending on the membrane type and configuration.

Daily considerations include:

- concentrate stream from cross-flow membranes;
- backwash wastes;
- chemical-enhanced backwash wastes.

Batch considerations (from daily to annually) include:

- chemical clean residuals: maintenance cleans, CIP and including the final rinse water;
- run to waste.

8.6.3 Upstream considerations

Membrane filtration is very dependent on upstream water quality. Any negative changes to upstream water quality, such as algal blooms, or increased turbidity can cause premature clogging of membranes and require more frequent backwashing and chemical cleaning. This can negatively impact on the deployable output of the plant as follows:

- Changes in temperature and pH can result in changes in membrane performance.
- Changes in turbidity can result in changes in membrane performance and necessitate alteration to cleaning frequencies.

- Changes in feed pressure.
- Changes in incoming water salinity can result in changes in RO membrane performance.
- RO systems can become fouled if precipitates and scale form on the membrane. Precipitates and scale would not yet exist as removable particles at the time they pass through the pre-filter.
- Operation, settings or failures of other system equipment such as pumps, control valves, brine, pre-filtration, seals, module couplers, etc., can affect membrane system performance.

8.6.4 Downstream considerations

Membranes systems suit continuous operation where possible.

Consideration should be given to:

- sourcing and storage of backwash water and water for chemical cleans;
- the potential requirement for downstream dosing for conditioning purposes (e.g. remineralisation following RO applications), or any distribution network requirements (i.e. phosphate, fluoride, chlorine for secondary disinfection) and the management of these processes.

8.7 Process Start-up and Shutdown

8.7.1 General guidance

A structured start-up sequence is beneficial to avoid any pressure or hydraulic shock to the membranes. General considerations for start-up include:

- Ensure that any debris and/or foulants in the feed pipework have been flushed.
- Flush any accumulated air from the membrane elements and vessels with a gentle water stream.
- Any pumps on the feed site should be started up gradually and ramped up to the target operational flow rates in a slow and controlled manner.
- Flushing any residual cleaning chemicals from the system.

8.7.2 Consideration for new membrane modules

As identified in Section 8.4.6 on membrane module replacement, membrane modules are typically shipped in a sealed bag to maintain integrity. The bags often contain a small disinfectant (such as sodium bisulphite), glycerine or a proprietary solution.

Any large-scale replacement of membrane modules can be a challenge, particularly for small sites with limited waste stream processing capacity. Therefore, large-scale membrane replacements should be planned paying due consideration to:

- estimated waste volumes to be completed and whether or not temporary on-site storage and/or tankering is required;
- whether or not it will be necessary to stagger skid replacement to minimise strain on the DWTP flush water and waste residual resources.

8.7.3 Long-term shutdown and start-up

Membrane modules are typically not suited to long-term storage on-site, and care must be taken to maintain membrane integrity during any long-term shutdowns. Where excessive filtration capacity is present on a site, units should be constantly rotated to avoid a single unit not operating for a period of time.

Consideration must be given to the following:

- Maintaining water level in process units: most membranes must be kept fully wetted.
- Control of biological growth: if material compatibility allows, membranes are typically soaked in a concentrated sodium hypochlorite solution.

Each DWTP with a membrane should maintain a procedure outlining the actions required for medium- (24–48 hours) and long-term (> 48 hours) shutdown.

8.8 Process Troubleshooting

A review of potential issues, areas of investigative action and corrective action for membranes is provided in Table. 8.4. These identified issues should not be considered exhaustive but should be used to develop local operational procedures.

Generally, issues will fall into these broad categories:

1. feed water quality;
2. membrane module integrity;
3. membrane skid;
4. chemical clean.

Table 8.4: Malfunction: issues, investigations and corrective actions for membrane filtration

Issue	Recommended investigative action	Potential corrective action
TMP increase on membrane skid has started to increase more rapidly	Confirm feed water quality. Have there been any changes or potential introduction of a foulant (i.e. elevated organics, seasonal algal bloom, overdosing of upstream chemicals, etc)? Review membrane asset age Confirm effectiveness of backwash and chemical clean sequence in reducing TMP	Consider an extended chemical wash (if applicable) to recover Review membrane records and determine if membrane replacement may be required Optimise any upstream treatment processes Consider increasing frequency of backwashing and/or chemical clean
Deterioration of feed water quality	Determine if upstream intervention is possible to improve feed water quality	Consider adjusting backwash frequency Consider increasing frequency of chemical cleans Consider adjusting chemical clean sequence (long duration, stronger chemical)

Issue	Recommended investigative action	Potential corrective action
Detection of elevated turbidity and/or detection of pathogenic organism(s) in filtered water	Review integrity testing profiles. Confirm that integrity testing has been completed satisfactorily Inspect all membrane skids. Confirm that all valves are in satisfactory order and that there is no risk of any bypass or seepage	Repair and replacement of membrane modules when necessary, then repeat checks for the original issue in filtered water
Inadequate treated flow rates from membrane units	Review TMP trends of membranes, including before and after chemical cleans have been completed Confirm satisfactory operation of backwash system Determine if issue applies to all skids, or a single skid	Consider chemical clean
Residual of cleaning chemicals in membrane modules	Confirm pH and conductivity profiles before, during and after the clean sequence Confirm satisfactory dosing quantities of cleaning chemical(s) Consider initiation of cleaning sequence supported by manual sampling	Consider altering parameters on the control panel for chemical cleaning Corrective action as required for dosing equipment and associated control valves
Poor performance from membranes observed after shutdown	Indicates an issue with fouling and/or scaling of the membranes Confirm shutdown methodology used	Consider chemical clean
High conductivity in permeate	Confirm if the issue is universal (all membrane skids) which indicates membrane damage Confirm if issue is on a specific pressure valve, which could indicate an O-ring issue	Repair to/replacement of O-ring as required Corrective action to membrane skid
High rate of fibre breakage observed	Check pressure and any risks of water hammer Confirm that there has not been exposure to incompatible chemicals (or concentration) or excessive temperatures Confirm sufficient pre-treatment Confirm quality of chemical clean chemicals Confirm membrane age and that modules were stored appropriately during any shutdowns	Consider third-party analysis/membrane autopsy in consultation with membrane supplier Consider warranty claim

Issue	Recommended investigative action	Potential corrective action
Chemical clean does not return unit to baseline TMP	Evaluate cleaning sequence Confirm integrity of chemical dosing chemicals Determine if there is a risk that inorganic scaling has occurred. Soft water or an antiscalant may be required where high pH is used Confirm that flux is within design range	Verify and review cleaning sequence

8.9 Advantages and Limitations

Advantages are as follows:

- The site footprint required is smaller than in conventional filtration plants.
- Usually requires less chemical addition than conventional filtration plants.
- Technically can provide full treatment for multiple objectives (i.e. disinfection barrier, organic removal) in a single process unit.
- Process can be easily automated and requires less on-site intervention. Can be favourable for remote operations.
- Modern designs allow for operation at low pressures, which can make the whole-life cost competitive compared with conventional filtration plants.

Limitations are as follows:

- Capital cost is often much greater than that of conventional filtration plants.
- Although less hands-on labour is often required, specialist knowledge is required to effectively manage and troubleshoot a membrane plant.
- Technology can be energy intensive. The greater the operating pressure, the higher the energy costs will be.
- Backwashing and chemical cleaning can provide waste volumes that require special treatment (e.g. pH neutralisation).
- High-quality feed water is required to avoid premature fouling of membranes.
- Poor operation can lead to premature irreversible fouling, which will shorten the lifespan of a membrane module.
- Scaling on the membrane surface can be an issue with hardness or high iron and/or manganese levels in the feed water.

9. PRE-TREATMENT FILTRATION TECHNOLOGIES

9.1 Overview

This chapter provides a brief overview on coarse filtration technologies that are used upstream of conventional treatment plants (i.e. raw water screens, roughing filters, bankside filtration).

9.1.1 Filtration objectives

Pre-treatment filtration technologies are generally used for the following:

- **Downstream protection**: pre-filtration technologies are generally installed to provide protection for downstream processes and mechanical equipment (e.g. pumps and valves), typically by providing removal of suspended solids.
- **Turbidity removal**: some pre-filtration technologies are installed to provide a barrier for turbidity and ensure that a turbidity target is achieved for downstream processes.

9.1.2 Guidance on log removal credits

Pre-filtration technologies are generally not considered a protozoan barrier.

9.2 Microstrainers

Microstrainers are revolving drums that contain a straining medium, which is typically a fine metal mesh. The drums are generally 75% submerged in the feed water, typically in an open tank, and are rotated. Water enters axially and flows out of the drum radially, leaving any filtered matter on the screen material. The screen is backwashed by pressured water jets.

Microstrainers provide physical removal only. They have been installed for management of source water where biological organisms, such as zooplankton and algae, are an issue. However, many installations in Ireland have often proven to have limited effectiveness for algae.

The New Zealand regulations allow for up to a 0.5 protozoan log removal credit for some micro-strainers. The exact criteria are outlined in the *Guidelines for Drinking-water Quality Management for New Zealand* (New Zealand Ministry of Health, 2017).

9.2.1 General design and operational considerations

The following should be taken into consideration in the design and operation of microstrainers:

- The pumping well may be infiltrated from shallow groundwater that did not receive the same degree of filtration in the subsurface environment as the targeted surface water source.
- Head loss should be measured continuously.
- It requires very frequent backwashing at 2 bar pressure to keep the mesh clean. Consideration should be given to providing a continuous source of water for flushing. The required flush water can equate to 3–5% of the throughput.
- Removal of total algae typically ranges from 50% to 75% (Twort, 2016).

When algae or leaves have to be removed, a microstrainer may be considered. The basic system consists of a revolving stainless steel wire mesh drum, with apertures from 20 to 50 µm depending on the algae to be removed. The raw water enters the drum axially and passes by gravity through the cylindrical mesh body as it rotates. Such units have been used with varying degrees of success to improve the raw water arriving at slow sand filter plants, thereby extending filter runs.

9.2.2 Advantages and limitations

The advantages of microstraining include the following:

- It is a simple process with limited requirement for manual intervention. It is also fully automatic.
- Head loss is sufficient to monitor process.
- Can be installed downstream of GAC applications, where biological growth or release of media fines is an issue.

The limitations include:

- It provides removal of particulates only.
- The microstrainer can be damaged if loading exceeds the capacity of unit. This risk can be mitigated with the installation of a fail-safe bypass weir and/or process shutdown alarm. However, when active, a bypass weir will result in a deterioration of feed water quality.

9.3 Screens and Disc Filters

Typical examples of screen and disc filtration technologies include:

- Coarse intake screens: typically bar screens.
- Fine screens: usually mechanically cleaned as fine mesh can clog rapidly. Most commonly of the band and drum screen type. Apertures typically range from 6 to 9.5 mm, but some finer installations of 0.5–5 mm are common.
- Washable disc filters: stacks of discs mounted one on top of the other. Gaps range between 5 and 100 µm. Filters require backwashing and typically require a regular (every 6–12 months) invasive clean and chemical soak.

9.3.1 General design and operational considerations

- The presence of aquatic life may require specific requirements regarding screen aperture and material selection.
- Where appropriate, head loss should be measured continuously.
- Provision must be made for the safe removal of debris trapped in the screening process. Thus, safe level access must be provided over the screen/filter with hand rails, fall arrestors etc., to protect personnel involved in the cleaning process.
- Consideration could also be given to installing an air-burst facility to keep screens/filters clean where appropriate for the technology.
- Consideration should be given to the requirement for spare screens or duty standby arrangements as appropriate.

9.3.2 Advantages and limitations

The advantages of screen and disc filtration technologies include the following:

- They provide vital protection for downstream treatment assets.
- The technology is simple and, when automated, requires minimal manual intervention.
- They are easy to use and monitor. No specialist training is required.

The limitations include:

- Biological fouling can impede screen performance.
- Providing suitable access for maintenance can be challenging.
- Rapid blinding can occur as a result of changes in source water quality.

9.4 Bank Filtration

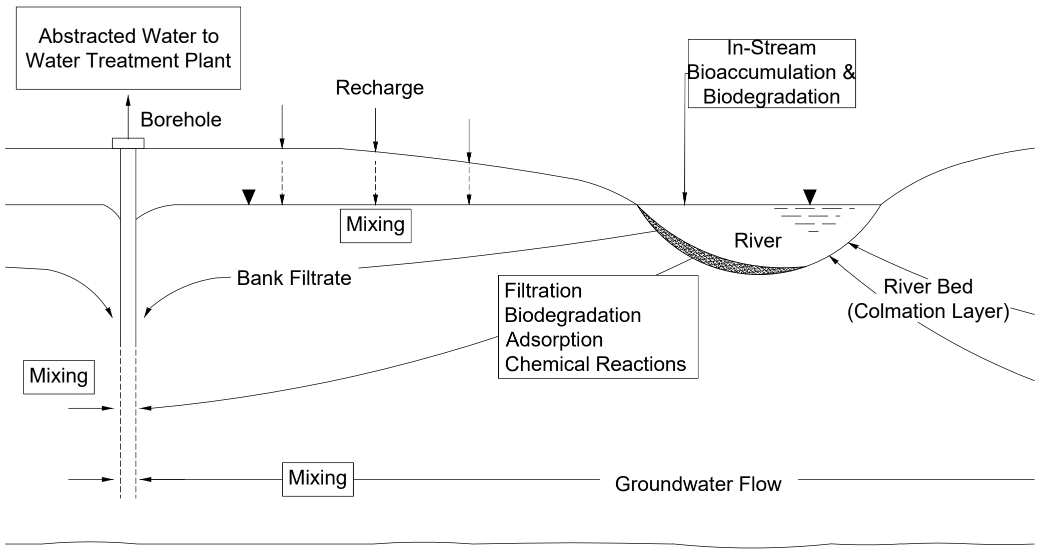
Bankside filtration is a pre-treatment process that involves using the bed and/or bank of a river/lake and its adjacent aquifer as a natural filter. The systems can be:

- Natural: in this case the natural properties of the surface water bed and aquifer are unmodified with the exception of allowance for a pumping well.
- Engineered: these systems are often coupled with aquifer recharge and/or storage operations, in which the water flows through a constructed pathway and/or installed media.

The technologies can be very effective at reducing the concentration of suspended particles from the surface water. There are limited applications of bankside filtration and infiltration galleries in Ireland currently.

An example process overview is provided in Figure 9.1.

Figure 9.1: Overview of bank filtration.



The New Zealand regulations allow for up to a 0.5 protozoan log removal credit, but the installation must meet specific criteria as outlined in their guidance document (New Zealand Ministry of Health, 2017). These log credits are generally only achievable by engineered solutions.

Infiltration galleries may be seen as similar to bank filtration processes; however, they generally do not provide controlled filtration within the subsurface environment. They should not be considered as bank filtration processes and therefore are also not eligible for pathogen removal log credits.

9.4.1 General design and operational considerations

The following should be considered in the design and operation of bank filtration:

- The pumping well may be infiltrated from shallow groundwater that did not receive the same degree of filtration in the subsurface environment as the targeted surface water source.
- The rate of infiltration should be calculated and considered. The lower the loading rate, the better the treatment; however, the yield of filtered water is also lower.
- The distance between the well (point of abstraction) and the riverbank.
- Travel time (retention time) through the bank filtration system.

9.4.2 Advantages and limitations

Potential advantages of bankside filtration include:

- It can be a low-cost technology.
- It provides for reduction in TOC, pathogens and turbidity. It can also provide more stable water quality to downstream water treatment processes.

Potential limitations include:

- Suitability is dependent on site-specific conditions.
- Pore clogging of the riverbed material can reduce the hydraulic yield of the system.
- Aeration may be required because of depletion of oxygen from biological activity.
- Anaerobic conditions can lead to the release of manganese and iron from the bank sediment and require additional downstream treatment.
- It is vulnerable to flooding and drought conditions at the surface water source.

9.5 Roughing Filters

Roughing filters are typically media filters, conventional gravity and pressure filtration applications that are not designed or operated to provide a protozoa barrier.

Typical examples include:

- Pre-treatment filtration provided for sources that occasionally experience raw water quality changes and require a filtration barrier to achieve downstream targets (i.e. below 0.2 NTU pre-disinfection).
- Media filters installed to prevent premature clogging for downstream filtration process, such as slow sand filtration, cartridge filtration and membrane filtration processes.

9.5.1 General design and operational considerations

- Chapter 5 on rapid gravity and pressure filtration will generally apply; however, these filters can often be operating at higher loading rates (i.e. > 10 m/h) and filter run times.

- Consideration should be given to process resilience requirements including duty standby arrangements.
- Consideration of modular packaged systems is provided in Chapter 10.

9.5.2 Advantages and limitations

Advantages of roughing filters include:

- They are typically fully automated and require minimal intervention.
- Their use can extend the operating cycles of downstream filtration processes that provide a protozoan barrier.
- They provide a reliable upstream barrier to protect downstream treatment processes.
- They can be retrofitted into existing treatment processes.
- They can be operated seasonally, if required by source water quality.

Specific limitations to consider, depending on the technology selected, include:

- washwater and process residuals require management.
- Determination of optimal loading rates and operating criteria often requires in-depth knowledge of water quality variability. A more conservative design approach is recommended.
- Seasonal operation requires careful operational controls to mitigate risk of biological growth within the filtration media while maintained offline.

10. ALTERNATIVE AND EMERGING FILTRATION TECHNOLOGIES

10.1 Overview

This chapter provides an overview of alternative filtration technologies that either have established use in other international jurisdictions or are an emerging technology and potential use in Ireland in the future is considered likely.

Ion exchange and powdered activated carbon have not been included in this manual. Although these technologies are an example of adsorption (a core filtration mechanism), they are not generally classified as a filtration technology and are implemented for the treatment of soluble compounds only.

10.2 Alternative Filtration Media

Alternative filtration media are engineered media designed to replace sand and/or anthracite in conventional media filtration applications. Examples include:

- glass media – often made from recycled glass;
- engineered ceramic media;
- zeolites (microporous aluminosilicate minerals that are effective adsorbents).

The media are often engineered to have increased angularity, which allows for greater surface area than conventional media. In addition, the media properties, especially in the case of media intended to replace anthracite, provide a more robust material with a longer lifespan.

Zeolites are a relatively new technology and are the subject of ongoing development. Given their adsorptive capacity they have the potential to be added to media filtration for targeted adsorption of organic compounds including pesticides.

10.2.1 General design and operational considerations

- The main challenge associated with the implementation of alternative media is the lack of widespread information and application-specific guidance.
- It is often advantageous to complete a pilot trial or a long-term full-scale trial in which a single filter at a water treatment facility receives the new media. It is critical that sufficient monitoring be in place to ensure that water quality is not jeopardised during the trial period.
- It can be difficult to quantify the performance benefit from alternative media, given that filtration performance is generally measured by turbidity and filter run times. The benefit of the media may be a reduction in whole-life cost if the engineered media has a longer effective working life, can provide process benefits such as extended filter run times or can negate the requirement for downstream processes.
- Care must be given to applications where media is retrofitted into existing filters. The new media is likely to have a different density, meaning that the bed expansion may not be the same as when conventional media are used, for the same backwash flow rate. Designers must ensure that sufficient bed expansion can be achieved while also ensuring that no media is lost as a result of excessive backwash rates.
- Operational practices are generally not affected by changing from conventional media to alternative media.

- The critical control parameters identified in Chapter 5 on RGF and pressure filtration generally apply. Additional considerations should be given to media that is installed to target adsorption of a particular compound.

10.2.2 Advantages and limitations

The advantages of alternative filter media include:

- The media is engineered, meaning that the media size can be tailored to specific applications.
- Media may be derived from recycled material, lowering the carbon footprint of the installation.

Potential limitations include:

- The capital cost is often greater than that of conventional media. Performance benefits may be difficult to accurately quantify to complete an effective whole-life cost–benefit analysis.
- Media properties may require alterations to backwash systems to ensure that an adequate backwash regime is maintained.

10.3 Adsorption Applications for Metals Removal

Adsorptive media can be used for targeted metals removal and is a well-established treatment technology. Two common applications include:

- activated alumina (fluoride, arsenic and selenium);
- iron oxide-coated media (sand, activated carbon) for arsenic removal.

There are many examples of proprietary engineered media that target the above compounds and other metals using the basic filtration mechanism of adsorption. The media is typically encased within a gravity or pressure filter-type layout.

10.3.1 General design and operational considerations

- The adsorption of targeted metals is pH dependent. For example, in the case of activated alumina for fluoride and arsenate [arsenic (V)] the pH optimum is 5.5–6.
- Competing ions may be an issue, including silica, fluoride, phosphate and sulphate. Activated alumina is generally more susceptible to adsorbing competing ions than iron-based media.

10.3.2 Advantages and limitations

Potential advantages of adsorptive media include:

- They provide a low-cost solution that requires minimal footprint.
- They can be retrofitted downstream of existing treatment processes for targeted contaminant removal.

Limitations of the technology include:

- Filtration media used often have limited adsorptive capacity and must be replaced at regular intervals.
- Backwashing wastes may be unsuitable for recycling to the head of the DWTP or may require additional treatment to allow for recycling to head of works.

10.4 Pre-coat Filtration

Pre-coat filtration involves applying a cake which acts a filter medium on a support structure. The most prevalent example for drinking water applications is diatomaceous earth (DE) filtration. DE is a fine powdered substance that is made of the skeletons of diatoms. When used in water filtration, DE is added to the feed water prior to each filter run to pre-coat a mesh screen (known as a septum) with a cake layer.

The process is generally applied to smaller DWTPs that have consistently good-quality source waters with low turbidity and colour. The process is generally not effective for soluble organic matter. The New Zealand Guidelines (2017) allow for a protozoa removal credit of 2.5 log credits.

10.4.1 General design and operational considerations

- DE is prepared for addition to the process in a slurry tank.
- For effective filtration, the filter cake must be built up on the septum. This requires the application of a high dose for a short duration (< 30 minutes) to target a minimum cake depth of 2–3 mm. Water is recirculated in the process until the pre-coat step is completed. A typical dose is 1 kg of DE per m^2 of filtration area.
- Filtration rates are generally between 2.9 and 4.3 m/h.
- The filter runs continuously with a small dose of DE continually applied (the dose is determined based on individual plant experience, but a rough starting point is approximately 0.15 kg/m^2/day).
- After the critical head loss or turbidity is achieved, the filter run must be stopped. The accumulated cake layer is removed from the septum and disposed of and the pre-coat process commences again.
- Traditional systems are vacuum driven.
- New systems involve pressure filters. These can run up to rates of 5.8 m/h.
- Similar to cartridge filters, the critical operating parameters are head loss and turbidity.
- Filter run times are typically between 1 day and several weeks.

10.4.2 Advantages and limitations

Potential advantages of DE filtration include:

- It is an effective low-cost filtration technology for small systems.
- There are no requirements for backwash and there is no liquid discharge.

Limitations include:

- DE filter media is typically sourced from the Unites States and may not be a viable option.
- Optimising filtration requires correlating the required DE dose with turbidity. This can present an issue for source waters with variable turbidity. The application is best suited to stable sources.
- Spent DE cake must be disposed off-site, typically to landfill.
- DE is a finely powdered material and can cause respiratory issues. Special handling procedures are required.
- Filtered water must be recycled during the pre-coat process.

10.5 Packaged Modular Filtration Solutions

There are increasingly more “packaged” filtration solutions available on the market. These technologies are varied but are generally based on the core principles outlined for the traditional media processes of RGF and pressure filtration applications, cartridge filtration or simple size exclusion screening. Examples include:

- Designs that allow high filtration rates (> 20 m/h) while maintaining a core performance guarantee. These applications are best suited for pre-treatment applications where the technology is not incorporated as a pathogen barrier.
- Designs with multiple types of media, sometimes with novel or alternative media.
- Proprietary designs with continuous backwash and or flushing applications.
- Various screening technologies that provide physical removal of particulates to protect downstream processes (e.g. clarification plants, membrane plants).

10.5.1 General design and operational considerations

- Technologies are packaged systems and are generally sized directly by the technology provider. Designers are accountable for understanding the feed water quality and should have sufficient data to understand the design.
- Consideration should be given to process resilience requirements including duty standby arrangements.
- Consideration should also be given to any cleaning requirements whether automated or manual.

10.5.2 Advantages and limitations

Advantages of the technology include:

- They are typically fully automated and require minimal intervention.
- Proprietary filtration systems may allow for a reduced footprint compared with conventionally designed processes.
- The provide a reliable upstream barrier to protect downstream treatment processes.

Specific limitations dependent on technology selection that should be considered include:

- Sizing of package systems requires the capture of sufficient operational water-quality data.
- Access to and availability of critical spares and replacement parts.
- Washwater and process residuals require management.

10.6 Ceramic Membranes

Ceramic membranes are currently used in MF/UF applications for drinking water. The technology is not new; however, previously the higher capital cost of the membrane modules compared with traditional polymer-based materials made the technology not whole-life cost-effective. However, as the technology is evolving, the cost is falling, and the technology is gaining increasing traction with installations in the United States, England, Singapore, the Netherlands and Japan, among other places. The technology is most widely implemented in Japan for drinking water, with over 100 plants in operation.[7] Equivalent log reduction to that presented in Section 8 on membrane filtration is expected.

7 https://pwntechnologies.com/pub-to-use-ceramic-membranes-for-more-efficient-water-treatment/

10.6.1 General design and operational considerations

- The approach to the design and implementation of ceramic membranes, core operational guidance and critical parameters are in line with the overview given in Chapter 8 on membrane filtration.
- Ceramic membranes are a rigid membrane structure. Direct integrity testing can be achieved only using size exclusion-based testing methodologies.

10.6.2 Advantages and limitations

The advantages of ceramic membranes compared with polymeric membranes are as follows:

- Ceramic material is stronger and more chemical resistant than polymeric membranes. This means that the membranes can be cleaned more aggressively. Some units may even be regenerated by removing fouling in higher temperature. Organic fouling will burn off at temperatures exceeding 550 °C.
- Ceramic membranes have a longer design life than polymeric membranes (typically 5–7 years) and are expected to last for the entire design life of the membrane plant.

Potential limitations of the technology include:

- The membranes are negatively charged, which means that can be very easily clogged where feed waters contain positively charged particles. They can also be more easily affected by the use of upstream chemicals and biofoulants (i.e. algae).
- Limited applications in drinking water mean that pilot testing is required to confirm key design aspects including flux, cleaning regime and cleaning frequencies.

10.7 Biological Filtration

Biological filtration is an emerging area of development, with increasing applications in North America. The technology is also included in the recent update to the *Guidelines for Drinking-water Quality Management for New Zealand* (New Zealand Ministry of Health, 2017). The process is defined as an operational practice of managing, maintaining and promoting biological activity on granular media in an aerobic environment (Water Research Foundation, 2017).

Biological filters are media filters, normally with GAC media, that encourage bacteria to establish populations within the media bed. This particular application is referred to as a biological active carbon (BAC) reactor. The microbial populations will consume natural organic matter and some synthetic organic compounds.

An oxidant is typically applied upstream of the filters. This is done to break down larger organic compounds into smaller, more readily biodegradable, components.

Standardised guidance for log removal credits is not yet available for the technology; however, applications that can meet the required criteria should expect to achieve log reduction equivalent to conventional and direct filtration applications.

10.7.1 General design and operational considerations

- Oxygen consumption within the reactor can require filtered water to be re-aerated.
- The life of GAC media is typically longer in BAC applications than in conventional GAC applications. This is attributed to fact that the predominant function of GAC media is to provide a porous support structure and the biological activity will consume some of what typically would have been adsorbed by the media in a non-biological application.
- Filtered water can contain high bacteria counts and this needs to be addressed in downstream disinfection processes.
- Filters are backwashed.
- The EBCT required is similar to that of GAC adsorbers, with a minimum of 15 minutes recommended.
- Monitoring tools have been identified in four core categories (Water Research Foundation, 2013):
    1. Biological: bacterial concentration and/or activity [e.g. heterotrophic plate count (HPC), dissolved oxygen].
    2. Organic carbon: measurements of the different fractions or types or organics (e.g. TOC/DOC).
    3. Water quality: physical and chemical characteristics of water (e.g. turbidity).
    4. Operational: general process monitoring parameters (e.g. head loss, chlorine demand).

Additional information can be found in the *Biological Filtration Monitoring and Control Toolbox: Guidance Manual* (Water Research Foundation, 2013). Some outline guidance is available in the *Guidelines for Drinking-water Quality Management for New Zealand* (New Zealand Ministry of Health, 2017) with respect to BAC.

10.7.2 Advantages and limitations

Advantages of the technology include:

- It can be an effective technology to reduce numerous target compounds within a single process stage.
- Existing filtration processes can be retrofitted. Current research (Water Research Foundation, 2017) has focused on providing structured guidance for managing the conversion to biofiltration.
- It has proven to be effective in managing taste and odour and reducing the formation of DBPs.
- It can be an effective barrier against manganese, as some biological processes consume manganese.
- Conversion of a traditional filter to a biological filter could avoid the need for installation of additional treatment processes.
- The biological activity may negate the requirement to regenerate or replace exhausted media (i.e. GAC).

Limitations of the technology are:

- It can lead to an increase in some measured bacteria, such as HPC.
- Research and information related to optimising the biological activity are limited. Sampling required can be expensive and rapid turnaround may be a challenge.

- Optimisation is site specific.
- Design frameworks for full-scale operations are currently under development.
- Adverse conditions can lead to destruction of biological activity, which will require time to restore to former levels and can lead to suboptimal filtered water quality. It can take 2 weeks to 6 months for biological activity to be fully optimised (Water Research Foundation, 2017).
- Upstream oxidant often needs to be dosed.

10.8 Slow Sand Filtration with Backwash

In the early 2000s, an alternative to the traditional slow sand filtration process was patented by Manz Engineering Ltd. Often referred to as a "Manz slow sand filter", the technique involves slow sand filtration that can be operated either continuously or on demand as required and allows cleaning using a backwash.

The first iteration of the technology focused on small-scale individual households and has been widely implemented, particularly in developing countries. A community-scale version of the technology is now marketed by Manz Engineering Ltd.

10.8.1 General design and operational considerations

- The current patent provider provides a package modular system. Piloting of the technology is recommended.
- The purpose of the backwash is to fluidise the upper layer of the slow sand filter (i.e. the *schmutzdecke*). The upflow rates during the backwash are therefore less than that required for media filtration and air scour is not used.
- Backwash water must be free of any disinfectant residual to protect the *schmutzdecke*.
- The minimum design life of the media bed is 10 years.
- Run to waste following from backwash can be incorporated into the design.
- Loading rates of over 1 m/h (compared with the recommended 0.3 m/h) for traditional slow sand are quoted; however, this does not account for any regulatory restrictions or consideration for achievable log removal credits.
- The filters do not require continuous flow. They can be left under aerobic conditions and operated on demand.

10.8.2 Advantages and limitations

Advantages of the technology include:

- Although a modular system, the current technical literature indicates that catering for capacities in excess of 24 MLD is realistic.
- The volume of backwash water that is required is estimated to be 1% of the filtered water produced, which is far less than the ≥ 5% required for conventional media filters.
- Cleaning is less labour-intensive for the operator than cleaning/scraping of traditional slow sand filters.
- It is suitable for GAC and iron and manganese removal applications.
- The footprint required is less than that of traditional slow sand filters.
- It can tolerate a higher solids loading than traditional slow sand filters (> 5 mg/l).

Potential limitations of the technology include:

- Very few case studies are available, particularly for large-scale installations. Although capacities in excess of 24 MLD have been quoted (Manz Engineering Ltd, 2013), most case studies reference installations have throughput < 3 MLD.
- A pilot study is required at the source to optimise loading rates and backwash rates.
- Although more compact in footprint than traditional slow sand filtration, the technology will still require more footprint than a conventional filtration system.

10.9 Continuous Upward Flow Filters

In simple terms, conventional filtration comprises downward flow of water through a media bed. Solids are gradually accumulated in the media bed, progressively increasing head loss. Operation is interrupted to allow backwashing followed by resumption of filtration.

In contrast to conventional filtration, continuous upward flow sand filtration technology is available. First patented in 1974, the technology is now available from several different major international suppliers. The technology is typically supplied in prefabricated freestanding packaged units; however, the technology can also be built into concrete tanks.

10.9.1 General design and operational considerations

- In contrast to traditional sand and dual-media filters, raw water is injected at the bottom of the filter. Suspended solids are filtered out as the water travels upward through the media bed.
- The filter is backwashed continually as it operates. A small portion of the filtrate produced is collected and used to backwash the filter.
- The continuous backwash is completed using an air lift pump, which collects media from the bottom of the filter. The media is drawn upwards into a wash box which separates filter media from any accumulated solids. Washed sand is returned to the media bed and the removed solids are diverted out of the wash box as waste. This takes place simultaneously with the operation of the filter.
- There is also the option to operate the backwash mode intermittently. This backwash is completed while the filter is still producing water for supply.

10.9.2 Advantages and limitations

Advantages of the technology include:

- Backwash is continuous, meaning that no offline time is required for backwash.
- No requirement for backwash storage tank.
- Maintenance requirements are low as there are no moving mechanical parts.

Specific limitations dependent on technology selection that should be considered include:

- Continuous operation of the air lift pump means that energy demand is higher than in the case of conventional filtration.

Glossary and Definitions

Absorption – permeation or dissolution of a substance into the body of another by molecular or chemical action.

Activated carbon –carbon that has been heated, or chemically treated, to increase its adsorptive capacity. The carbon is processed to have small, low-volume pores that increase the surface area available for adsorption and/or other chemical reactions.

Adsorption – a physical or chemical mechanism in which a compound (gas or liquid) is gathered on the physical surface of a medium. This can be on the filter media itself, or previously deposited and/or adsorbed particles.

Air binding (locking) – the clogging of a filter, pipe or pump owing to the presence of air released from water. Air contained in the filter media can prevent the passage of water during the filtration process. This can cause the loss of filter media during backwash.

Air integrity test – direct integrity-testing methodology completed on porous membranes. This involves measuring the air pressure loss across a wetted membrane over a defined time interval.

Algae – primitive organisms that contain chlorophyll and, therefore, are usually classified as plants. There are hundreds of species, many of which are microscopic. When present to excess, algae can cause issues in water treatment by clogging filters.

American National Standards Institute (ANSI) – an organisation that publishes American and international standards for multiple industries.

Anthracite – a hard, natural coal that is nearly entirely carbon based.

BAC - biological active carbon

Backwashing – the process of reversing flow of water (either alone or in combination with air) through a filter media bed to remove entrapped particulates.

Bacteria – microorganisms, often composed of single cells shaped like rods, spheres or spiral structures, which are ubiquitous in all habitats on Earth including water, and which range in size from 1 to 5 µm.

BAF - biologically active filtration

Barrier – a treatment or disinfection process that constitutes an impediment to the transmission of waterborne pathogenic microorganisms or other contaminants to humans in drinking water. The term "barrier" encompasses treatment and disinfection processes that either remove or inactivate such microorganisms and contaminants.

Bed volume (BV) – the minimum volume of water required to fully wet the media bed, or the volume of water that occupies the media bed when it is fully submerged.

Breakthrough – passage of floc, organism or a substance targeted for removal, above the targeted allowable limit through a filter media bed.

CA – cellulose acetate

CEB - chemical-enhanced backwash

Coagulation – the use of metallic salts (e.g. aluminium or iron) and/or organic polyelectrolytes to aggregate suspended or colloidal particles, causing them to agglomerate into larger particulate flocs.

Colloids – a type of very small, finely divided particulate matter, ranging in size from approximately 2 to 1000 nm in diameter, which can be present in water. Colloids do not settle out rapidly and remain dispersed in a liquid for a long time because of their small size and electrical charge, which causes them to repel each other. Repulsion of similarly charged particles can prevent the particles from becoming heavier and settling out.

CFC – coagulation, flocculation and clarification

Chlorophyll a – a pigment that makes plants and algae green. Often measured in source and treated water as a surrogate for algae.

Clarification – a water treatment process that separates liquids and solids through sedimentation (settlement) or floatation of the solids. Solids are flocs and particulates that were formed and enlarged in upstream coagulation and flocculation.

Clean-in-place (CIP) – the chemical cleaning of membranes as an online process. Membranes are cleaned within their installed skids, without removing them from the system.

Colony-forming unit (CFU) – a unit used in microbiology to estimate the number of viable organisms in a sample.

Colour – an attribute of source waters typically due to the presence of organic compounds and/or colloidal metal (i.e. iron, manganese).

Conventional water treatment – the term used by many international regulatory agencies to describe a water treatment plant that contains coagulation, (possibly) flocculation, clarification and filtration.

Cryptosporidium – a parasitic protozoan found in the intestinal tract of many vertebrates. Many species exist, including *Cryptosporidium parvum (C. parvum)*, which is infectious to humans. The environmentally resistant, transmittable form is called an oocyst. It is excreted in the faeces of an infected host. *C. parvum* can be present in source water from the excrement of livestock, including cows and sheep.

CSTR - continuous stirred tank reactor

Cyst – the resting or dormant stage of a microorganism, which helps the organism survive in unfavourable environmental conditions.

d_{10} - the sieve aperture size through which 10% of the filter media (measured by weight) can pass. The d10 value is also called the effective size (ES).

d_{90} - the sieve aperture through which 90% of the media passes.

DE - diatomaceous earth

Direct filtration – a term used by many international regulatory agencies to describe a water treatment plant that carried out coagulation, and (possibly) flocculation, followed by filtration.

Direct integrity testing – a test to confirm that the integrity of a filter matrix has not been compromised. This includes air integrity testing for membranes.

Disinfection – the removal, deactivation or killing of pathogenic microorganisms.

Disinfection byproduct (DBP) – an undesired chemical compound formed during the disinfection process at a drinking water treatment plant (i.e. chlorine addition, ozone addition). This includes trihalomethanes, bromate (oxidation of bromide) and halo-acetic acids. The majority are formed by reactions with naturally occurring organic and inorganic matter water.

Drinking water treatment plant (DWTP) – a treatment facility at which treatment processes are carried out to provide final treated water to a distribution network.

DWSP - drinking water safety plan

EBCT - empty bed contact time

Effective size (d_{10}) (ES) – the diameter of particles in granular media, for which 10% of the total grains are smaller and 90% are larger.

Empty bed contact time (EBCT) – a measure of the time during which water to be treated is in contact with the treatment medium contained within a vessel. EBCT is equal to the volume of the empty bed divided by the flow rate.

Enmeshed – used to describe particles that have become entangled (integrated) to form larger agglomerations of particles.

EPA - Environmental Protection Agency

ES - effective size

Feed water – water that feeds into (i.e. the inlet for) a water treatment process. For example, outlet water from a dissolved air flotation process is the feed water to downstream rapid gravity filtration processes.

Floc – the fine, spongy particles that form in water to which a coagulant has been added. The particles are largely hydroxides, commonly of aluminium or iron. They accelerate the settlement of suspended particles by adhering to the particles and neutralising such negative charges as may be present.

Flocculation – a process to enhance agglomeration or collection of smaller floc particles into larger, more easily settleable particles through gentle stirring by hydraulic or mechanical means following chemical addition of aluminium or iron salts, and polyelectrolytes.

Fluidised – a filter media bed is suspended and kept in motion with an upwards flow of water (or water and air), as is done during a filter backwash sequence.

GAC - granular activated carbon

Garnet – a group of hard, reddish, glassy, mineral sands made up of silicates of base metals (i.e. calcium, magnesium, iron and manganese). Garnet is a higher density media than sand.

Geosmin – an organic compound with a distinct earthy flavour and aroma. It is produced from certain types of bacteria.

Giardia lamblia –a protozoan capable of infecting humans. It causes intestinal infection known as giardiasis.

Hazen scale – the platinum–cobalt (Pt/Co) scale for colour measurement. It ranges from 0 to 500, with 0 being the colour of distilled water.

Head loss – the head, pressure or energy lost by water flowing in a pipe, in a channel or through a tank as a result of turbulence caused by the velocity of the flowing water and the roughness of the pipe, channel walls or restrictions caused fittings. Water flowing in a pipe or channel loses head, pressure or energy as a result of friction losses. The head loss through a filter is due to friction losses caused by material building up on the surface or in the interstices of the filter media.

Head of the drinking water treatment plant – a location in a drinking water treatment plant prior to treatment, often referred to as 'head of the works'. This location is generally post coarse raw water screening and prior to any other process/chemical dosing.

Heterotrophic plate count (HPC) – also known as standard plate count, this is a measure of colony formation on culture media of heterotrophic bacteria in drinking water. It can be used to measure the overall bacteriological quality of drinking water.

Humic acid – organic substances that are part of humus (the major organic fraction of soil, peat and coal). They contribute to colour and organic loading in source water to a drinking water treatment plant. They are reactive with chlorine and will cause the formation of disinfection by-products when chlorine is dosed.

Hydraulic retention time (HRT) – a measure of the average length of time that a liquid remains in a water-retaining structure obtained by dividing the tank volume by the influent flow rate.

Hydraulic shock – disruption to a process unit due to a sudden change in velocity (i.e. flow rate through the vessel). Can also refer to a pressure surge caused by water that has been forced to stop or change direction abruptly.

Inactivation – of an organism, killed or rendered unable to metabolise or reproduce, and therefore no longer a pathogenic threat

Indirect integrity testing –monitoring of parameters that, when exceeded, probably indicate an issue with integrity of the filter matrix (i.e. differential pressure monitoring for cartridge filters).

Inorganic – **a** chemical substances of mineral origin, such as sand, salt and iron.

Interface – a boundary layer between two substances, such as water and sand filter media. The term applies to any liquid, solid or gas.

LMH – $l/h/m^2$. The unit of measurement of membrane flux in membrane filters. This is a measurement of the filtrate flow per unit of membrane filtration area.

Log credit – a credit that expresses the percentage removal and/or inactivation of a targeted pathogenic organism from drinking water.

m/h – m^3 per m^2 per hour

MCF – membrane cartridge filter.

MF - microfiltration

MLD - million litres per day.

Micropollutants – organic substances whose toxic, persistent and bio-accumulative properties may have a negative effect on the environment and/or living organisms.

MWCO - molecular weight cut-off

National Science Foundation (NSF) – an organisation that independently tests, audits and certifies for the food, water, health science, sustainability and consumer product sectors.

NDP - net driving pressure

NF - nanofiltration

Normalised clean bed head (NCBH) loss: a profile of head loss within a filter that facilitates comparison of head loss for each run cycle for the same filter.

NTU – nephelometric turbidity unit, the unit of measure used for turbidity.

Octanol–water partition coefficient (K_{ow}) – a measure of the tendency of a compound to move from the liquid phase into lipids. Determined by the ratio of concentrations of a target substance between two solvents: octanol and water.

Oocyst – a cyst containing a zygote of a parasitic organism. Oocysts are usually the most environmentally resistant form of an organism and are targeted for removal in drinking water treatment, given their resistant nature.

Oxidant – a substance that can oxidise other substances. Common oxidants used in water treatment include air, chlorine, potassium permanganate, chlorine dioxide and ozone.

Oxidise – to combine or become combined with oxygen.

Pathogen – a microorganism that can cause disease in humans, other organisms or animals and plants. Bacteria, viruses or protozoa may be pathogens and are in found in water, sewage, animal manure, farms and/or rural areas populated with domestic and/or wild animals.

PA - polyamide

PAC - powdered activated carbon

Permeability – the property of a barrier or media that allows a fluid (i.e. water) to diffuse through it without being chemically or physically affected.

pH – an expression of the intensity of the basic or acid condition of a solution. Mathematically, pH is the negative logarithm (base 10) of the hydrogen ion concentration, $[H^+]$. $[pH = \log (1/H^+)]$. The pH may range from 0 to 14, with 0 is most acidic, 14 most basic and 7 neutral. Naturally occurring waters usually have a pH between 6.5 and 8.5.

Plug flow – the travel of water through a tank, pipe, or treatment process unit in such a fashion that the entire mass or volume is discharged at exactly the theoretical detention time of the unit.

Polymer – a substance that has a molecular structure consisting predominantly of large molecules made of many smaller repeating molecules.

Pore – a small open void on a solid surface, such as granular media or a membrane surface, through which Gases, liquids and smaller particles can pass.

Porosity – the volume of void space to the overall volume of a material.

PP - polypropylene

Precursors – organic and inorganic impurities that can be converted into disinfection by-products following the addition of a disinfectant. For chlorination systems, precursors are generally derived from organic matter.

Primary disinfection – the treatment process element in which a chemical and/or physical barrier is used to achieve the necessary microbial removal and/or inactivation of pathogenic microorganisms in water

Primary filter – term that can be used to describe the first stage of filtration if the second stage is provided. These filters will generally provide the physical removal of pathogenic organisms.

Proprietary – supplied direct from the manufacturer/supplier to suit the specific context.

Protozoa – small, single-celled organisms, both free-living and parasitic, which feed on bacteria and organic matter.

PVDF - polyvinylidene fluoride

RGF – rapid gravity filtration.

RO - reverse osmosis

Schmutzdecke – a German word that translates as "layer of dirt". The layer forms in a slow sand filter and consists of a mixture of biological and solid matter, including bacteria, algae, protozoa and colloidal matter.

Second-stage filter – a filter that is installed downstream of another filtration processes. Such filters are most typically used for metals removal or reduction of organics (e.g. pesticide removal using granular activated carbon media).

Short-circuiting – refers to inconsistent retention time of water within a treatment process, meaning that there are inconsistent travel pathways from the inlet to the outlet of a process. Implies inadequate and/or suboptimal treatment.

SOP - standard operation procedures

Specific gravity – a ratio of the weight of a substance to the weight of an equal volume of water.

Synthetic organic compound – a man-made substance that contains carbon.

Slurry – a mixture of liquid and undissolved solids.

Terminal head – the head value at which a filter is taken out of service for backwashing.

TDS – total dissolved solids

TMP - transmembrane pressure

Total organic carbon (TOC) – the amount of carbon found in an organic compound. In drinking water, it reflects the total amount of organic matter that is present in the water. TOC in source water primarily originated from decaying natural organic matter (such as humic acids, fulvic acid, amines and urea), but also from synthetic sources (e.g. fertilisers, herbicides, industrial chemicals and chlorinated organics).

Trihalomethane (THM) – one of the family of organic compounds, named as derivatives of methane, wherein three of four hydrogen atoms in methane are each substituted by a halogen atom in the molecular structure. Formed in drinking water treatment when chlorine reacts with organic compounds.

Turbidity – the cloudiness or opaqueness of water caused by suspended solids. Most solids are typically not visible to the human eye.

UC - uniformity coefficient

UF - ultrafiltration

Ultraviolet transmissivity (UVT) – a measure of the fraction of incident light transmitted through a material (e.g. water sample or quartz sleeve). The UVT is usually reported for a wavelength of 254 nm and a path length of 1 cm. UVT is often represented as a percentage and is related to the UV absorbance (A_{254}) by the following equation (for a 1-cm path length):

$$\% \text{ UVT} = 100 \times (10 - A)$$

Unit run volume (URV) – the total volume of water filtered between backwash events.

US EPA - United States Environmental Protection Agency

Volatile organic compound – any organic chemical compound that, in its solid or liquid form, loses large numbers of molecules to the air (evaporates) at room temperature and normal atmospheric pressure.

Virgin media – new, unused, media, e.g. a newly installed sand and anthracite bed.

Viscosity – a physical property of a fluid. It is a measure of resistance to flow and describes the internal friction of a moving fluid. A fluid with a large viscosity will resist motion and is generally considered thicker. A low-viscosity fluid is often described as thin.

WHO - World Health Organization

Zygote – the earliest development stage of an organism that will lead to reproduction of the organism.

Appendix A – Drinking Water Safety Planning Hazards associated with Filtration

The following table provides a summary of example hazards and potential control measures for hazards that apply to filtration processes.

Hazard	Potential control
Frequent and significant flow variations through the works	Consider intermediate storage to smooth out flow variations. Ensure that processes are able to cope with fluctuations in flow. Verify with plant data.
Inadequate pre-treatment	Review design and ensure that appropriate treatment is in place.
Inadequate process control in place for filtration (e.g. lack of turbidity monitors)	Review design and monitoring requirements.
Inadequate particle removal due to overloading of the filters	Run filters within design and operating limits. Assess with turbidity measurements or particle counts.
Inadequate particle removal due to blocked filters	Run filters within design and operating limits. Set and operate appropriate backwash programmes. Assess by measurement of head loss, flow rate and turbidity
Inadequate particle removal due to inadequate filter media depth	Check appropriate media depth for design of filter. Maintain filters as per EPA guidance and filter design
Inadequate particle removal due to inadequate filter media type	Check appropriate media type for design of filter. Maintain filters as per EPA guidance and filter design
Inadequate particle removal due to inadequate backwashing regime (e.g. inadequate cycle length, uneven scour, pump failure, loss of filter media)	Set and operate appropriate backwash programmes. Regular inspection of filters and maintenance of backwash equipment
Inadequate particle removal due to poor filter maintenance (cracks, boils, etc.)	Regular inspection and maintenance programme. Replace filter media as appropriate
Rapid gravity filters put back into operation without slow start	Use slow start, delayed start or run to waste on filter return to service. Assess with turbidity measurements. Provide appropriate turbidity alarms

Hazard	Potential control
Slow sand filters put back into operation without ripening period causing inadequate particle removal	Check appropriate ripening regime in place. Assess with turbidity and coliform measurements
Filtered water – *Cryptosporidium* breakthrough	Ensure that turbidity monitors on each filter are routinely reviewed. Provide appropriate turbidity alarms and shutoffs
Filtered water – turbidity breakthrough > 0.2 NTU in sites where there is a risk of the presence of *Cryptosporidium* in the raw water	Run filters within design and operating limits. Assess with turbidity measurements provide appropriate alarms and shutoffs
Backwash water recycled to head of works causing increased turbidity	Monitor turbidity and flow rate on recycle flow line

Appendix B – Example Log Credit Calculations

The log credit approach is a mathematical means for expressing the removal and/or inactivation of organisms from water through treatment.

$$\text{log credit} = \log_{10}\{1/[1 - (\text{percentage removal}/100)]\}$$

Log removal	Percentage removal (%)
1.0	90
2.0	99
2.5	99.7
3.0	99.9
3.5	99.97
4.0	99.99
5.0	99.999

Example calculation: influent contains 1000 organisms, and outlet contains 30 organisms.

$$\frac{1000 - 30}{1000} = \frac{970}{1000} = 0.97 = 97\% \text{ removal}$$

$$\text{Log } 1000 - \log 30 = 3.0 - 1.48 = 1.52 \text{ log removal}$$

Example calculation: influent contains 100,000 organisms and outlet contains 10.

$$\frac{100{,}000 - 10}{100{,}000} = \frac{99{,}990}{100{,}000} = 0.9999 = 99.99\% \text{ removal}$$

$$\text{Log } 100{,}000 - \log 10 = 5.0 - 1.0 = 4 \text{ log removal}$$

Example calculation: influent contains 1000 organisms, and outlet contains 350.

$$\frac{1000 - 350}{1000} = \frac{650}{1000} = 0.65 = 65\% \text{ removal}$$

$$\text{Log } 1000 - \log 350 = 3.0 - 2.54 = 0.46 \text{ log removal}$$

Appendix C – Standard Operating Procedure Template

Organisation **DWTP Name**	**Standard Operating Procedure**	Approved by: Effective from: Version:
FILTRATION PROCESS		

For document control purposes, all procedures should provide clearly the person(s) involved in drafting, reviewing and approving the procedure, the approval date and the next required date of review.

1.0 Overview

State the general purpose of the procedure.

1.1 Process Objectives

Provide a succinct list of the primary process objectives for the filtration process. This should include primary treatment targets and objectives (e.g. log credit, turbidity targets), secondary objectives (e.g. metals residuals) and any other requirements that should be considered for downstream processes.

1.2 Process Description

A brief process description should be provided. Most Operation and Maintenance Manuals should provide a detailed process description as part of their control philosophy and/or general operating manual.

Details to be provided include:

- number of units;
- key process steps (e.g. forward filtration, return to service);
- outline of critical design information (e.g. number of units, maximum throughput per unit, media depth, design life of elements);
- any operational targets (e.g. filter run time, target for chemical cleans);
- inputs, outputs and process residuals;
- any chemicals required by the process;
- critical mechanical and electrical equipment (i.e. pumps, blowers, mechanical valves).

1.3 Operational Records

Provide an outline of where operational records are stored examples include:

- specific logbooks (i.e. process specific);
- alarm set points;
- SCADA telemetry data;
- process reviews;
- off-site review records (i.e. process optimisation reviews, SCADA data analysis).

2.0 Critical Control Parameters

The critical control parameters that apply to the filtration process should be captured in this section. An outline of a potential table is provided below.

A non-exhaustive list of control measures is as follows:

- continuous online monitoring with alarms;
- operational task at defined frequency;
- on-site testing;
- operational inspection;
- sampling for validation;
- automated plant shutdown.

Critical control parameter	Target	Significance	Defined control(s)
Name the water quality and/ or operational parameter	Provide target (or location of target)	Outline any significance (e.g. required for log credit, regulatory requirement, downstream protection)	List any relevant control measures in place to ensure achieving the target for the critical control parameters

2.1 Associated Instrumentation

A list of all instrumentation used for process monitoring and verifications should be provided. An example table is provided before.

Water treatment plant managers and operators may choose to list potential investigation and actions or refer to specific alarm response procedures.

Instrument	Location	Instrument loop time	Frequency of measurement	Configured alarms	Investigation when target not achieved	Potential corrective actions
Include type and location in process (i.e. individual filter turbidity)	Physical location of instrument	Estimate loop time, including travel and analysis time	Time interval between samples	List an alarms and process unit shutdowns configured		

2.2 Critical Spares

Any core requirements for critical spares and the process for managing them should be presented. Examples include spare cartridge filters, standby pumps, spare valves.

3.0 Operation

A general section on operations should be provided for the procedure.

3.1 Online Process Monitoring and Alarm Response

All instrumentation with configured alarms should be summarised. An example table is provided below.

Alarm	Investigations	Potential corrective action	Escalation trigger
Include type and location in process (i.e. individual filter turbidity)			Consider summarising any requirements for escalation, including time (i.e. turbidity > 1 NTU is a regulatory event)

3.2 *Visual Operational Checks*

Any routine operational tasks that are completed by the daily operational teams are considered.

Tasks	Task description	Task purpose	Frequency	Responsible person(s)	Escalation triggers

3.3 *Process Equipment Checks*

Any routine operational tasks that are completed by the daily operational teams are considered.

Tasks	Task description	Task purpose	Frequency	Responsible person(s)	Escalation triggers

3.4 *On-site Testing and Sampling*

Any requirements for on-site testing (i.e. daily water tests completed at on-site lab, samples collected for external analysis) should be provided here. A table similar to that provided for operational tasks could be considered.

Any escalation triggers for further operational response for any unsatisfactory results and/or associated response procedures should be identified in this section.

3.5 *Process Optimisation and Verification Reviews*

Any requirements for focused process review of the filtration process should be identified and summarised as appropriate. Example tasks include review of membrane cleaning frequency, filter inspections and media coring, etc.

3.6 *Critical Maintenance*

It is anticipated that most DWTPs will manage maintenance requirements (specifically for instrument calibration, Mechanical, Electrical, Instrumentation, Controls, Automation (MEICA) equipment, etc.) separately. However, any specific tasks and requirements that are not captured by alternative DWTP-documented procedures should be listed here.

Any relevant procedures for particular tasks should be listed in this section.

3.7 Process Consumables

Any specific requirements for process and management of consumables, including responsible/accountable persons, should be summarised.

Minimum storage requirements should be provided as appropriate.

3.8 Process Unit Start-up and Shutdown

Any specific requirements for start-up and shutdown, including any considerations for long-term shutdown, should be detailed. Examples include backwashing requirements for RGF after long-term outage, return to service after media change, etc.

4.0 Troubleshooting and Abnormal Operation

4.1 Troubleshooting

Any general troubleshooting guidance should be provided in this section. An example table has been provided:

Issue	Potential cause(s)	Recommended investigations	Potential corrective action

4.2 Abnormal Operation

Any abnormal operating conditions should be summarised. This could include action plans for poor source water quality, source water resource issues, algae blooms, energy failure, loss of telemetry systems, etc.

5.0 Roles and Responsibilities

A list/table of people and/or defined job functions and their core accountability and responsibilities should be provided. This includes any third-party companies that provide specialist maintenance and/or process reviews.

6.0 Associated Documents

A list/table of associated procedures including alarm response procedures should be provided.

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AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL

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

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

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

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

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

I measc ár gcuid freagrachtaí tá:

Ceadúnú

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

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

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

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

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

Bainistíocht Uisce

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

Eolaíocht Aeráide & Athrú Aeráide

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

Monatóireacht & Measúnú ar an gComhshaol

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

Taighde agus Forbairt Comhshaoil

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

Cosaint Raideolaíoch

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

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

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

Comhpháirtíocht agus líonrú

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

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

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

- An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
- An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
- An Oifig um Fhianaise agus Measúnú
- An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

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

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