

Chapter 13: Treatment processes, coagulation

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13.1 Introduction

This chapter covers the water treatment process of chemical coagulation, with or without sedimentation. It also covers the situation where sedimentation is not followed by rapid granular media filtration. The discussion on coagulation includes details of chemical coagulants and polyelectrolytes used in the process. The separate stages of coagulation: flocculation and conventional sedimentation (also called clarification) are included. In current terminology sedimentation is one of a number of processes that are grouped as clarification. New high-rate clarification processes, (lamella plates, tube settlers, buoyant media clarifiers, dissolved air flotation (DAF) and Actiflo®) are also covered in this chapter.

The discussion on filtration in this chapter covers only rapid gravity granular media filtration (pressure filters are used sometimes too). This is the most common filtration method following coagulation in use in New Zealand. Other filtration methods that do not normally involve coagulation, eg, diatomaceous earth, cartridge, slow sand and membrane filtration, are discussed separately in Chapter 14. Although coagulation is commonly practised with membrane filtration to remove colour, membrane filtration does not rely on coagulation for removal of protozoa and is therefore classified separately as filtration without coagulation, in terms of the *Drinking-water Standards for New Zealand 2005, revised 2008* (DWSNZ).

The combined process of coagulation and filtration is used commonly throughout New Zealand and is effective at removing dissolved and colloidal colour (natural organic matter), turbidity (suspended solids), algae (phytoplankton), bacteria, viruses and protozoa (eg, *Giardia* and *Cryptosporidium*). This treatment combination is often referred to as 'conventional treatment'.

The DWSNZ outline turbidity criteria and turbidity monitoring requirements that must be met by water treatment plants to ensure compliance with the protozoa criteria. Guidance on compliance with respect to coagulation and filtration is discussed in Chapter 8: Protozoa Compliance, section 8.3.2 of these Guidelines; this chapter concentrates more on operational aspects.

This chapter includes a section (section 13.6) that discusses lime softening. This usually operates at a pH that is high enough for calcium and magnesium salts to form a floc, so as well as softening the water, organic matter, turbidity and (oo)cysts can be removed. Therefore the process can earn protozoal log credits, see Chapter 8: Protozoal Compliance, section 8.4.2.1. Water softening (and other benefits) by using ion exchange is included in section 13.6 for completeness, although the process does not include coagulation and does not earn log credits. Softening is also discussed briefly in Chapter 18: Aesthetic Considerations, section 18.3, and in Chapter 19: Small, Individual and Roof Supplies, section 19.3.4.

The 2008 DWSNZ include a new section, section 5.17: Alternative processes: treatment compliance criteria, whereby water suppliers may apply to the Ministry of Health to have other treatment processes assessed for a log credit rating. This approach, which is explained more fully in section 8.4.5 of the Guidelines, allows water suppliers to apply for a log credit rating (or a variation to the prescribed log credits) for a treatment plant or process:

- a) not covered in sections 5.1–5.16 of the DWSNZ
- b) that performs demonstrably better than its compliance criteria
- c) that performs to a lesser, but reliable, level than specified in its compliance criteria.

Some process variation is normal and expected; however, too much variability can result in treatment failures, leading to waterborne disease outbreaks. An objective of the DWSNZ, therefore, is to keep process variability within acceptable limits. Understanding the causes of process variations should prevent recurrences. Problems may be able to be avoided and the time spent problem solving can be reduced by implementing an effective water safety plan (WSP – formerly known as public health risk management plans, PHRMPs).

Rapidly increasing plant production rates can cause sludge blanket disturbance and filter breakthrough. The main reason for this could be due to inadequate clear water storage at or near the water treatment plant (ideally at least 24-hour storage is recommended), or there is a need for more storage in the distribution system. The more consistent the treatment rate, the easier it is to maintain a good quality end product.

AWWA (2000) produced a series of manuals covering control of coagulation, filtration, softening, and the chemicals used for these, see full list at <http://www.awwa.org/files/Resources/Standards/StandardsSpreadsheet.xls>.

Risk management issues related to the treatment processes in this chapter are discussed in the:

- MoH Public Health Risk Management Plan Guide PHRMP Ref. P5.1: Treatment Processes – Coagulation/Flocculation/Sedimentation
- MoH Public Health Risk Management Plan Guide PHRMP Ref. P5.2: Treatment Processes – Dissolved Air Flotation
- MoH Public Health Risk Management Plan Guide PHRMP Ref. P5.3: Treatment Processes – Direct Filtration

- MoH Public Health Risk Management Plan Guide PHRMP Ref. P6.1: Treatment Processes – Rapid Sand Filtration
- MoH Public Health Risk Management Plan Guide PHRMP Ref. P8.1: Treatment Processes – pH Adjustment
- MoH Public Health Risk Management Plan Guide PHRMP Ref. P11: Treatment Processes – Plant Construction and Operation.

Records should be kept of all chemicals used in treatment processes. These should include the supplier, certification of the specification and grade of the chemical and datasheets, routine monitoring of the quality and standard of chemicals used, conditions of its supply and subsequent storage. Records of actual dosing of the chemical should show the chemical name, rates and quantity of the chemical dosed, the type and calibration of the equipment used. A method statement should give standard procedures in case of failure or breakdown of the system, with associated safety data sheets and Hazchem labelling for all chemicals used.

The Water Supply Managers' Committee of the New Zealand Water and Wastes Association (NZWWA) has been developing standards for chemicals used in water treatment. These cover aluminium sulphate, hydrated lime, three fluoride chemicals and three polyelectrolytes.

DWI (2011) has a list of chemicals that have been approved for use in water supply in the UK.

Documentation of the quality and quantity of chemicals used in the treatment process is important for the appraisal of the efficiency of the processes being used, and may affect which Priority 2 determinands are assigned to a supply and the frequency of sampling required for them.

The Hazardous Substances and New Organisms (HSNO) Act 1996 now controls the use of the following chemicals:

- chlorine gas
- calcium hypochlorite
- sulphuric acid
- hydrochloric acid
- sodium hydroxide
- aqua ammonia
- hydrogen peroxide
- potassium permanganate.

Since 1 October 2004 users may need a Location Test Certificate and/or an Approved Handler Test Certificate. Details are available by using the Step-by-Step Guide to Finding Controls and Other Useful Links at www.ermanz.govt.nz.

DWI (2013) investigated the incidence of impurities in chemicals used in the UK for water treatment. Chemicals used in the UK must be permitted under regulation 31 and normally this means the chemicals conform to a European or national standard, such as a BS EN, or the introduction or application of the chemical has been specifically approved by the Secretary of State. Unexpected contaminants can occur in chemicals even though they are compliant with the regulatory requirements. For example, a 2008 study found evidence of N-nitrosodimethylamine (NDMA) contamination of ferric coagulants (which otherwise conformed to the relevant BS EN standard). The use of this chemical gave rise to small but detectable concentrations of NDMA in drinking water. There were few reported concerns in the US about specific trace contaminants. The most frequent complaints were associated with gross contaminants, such as sediment or floating debris in liquid chemicals. While the source of the contamination was sometimes traced to a deficiency in the manufacturing or refining process, the most frequently reported incidents occurred during transport, primarily associated with improperly cleaned or maintained delivery containers or transfer hoses. DWI (2013) includes contaminant specs for several BS EN standards.

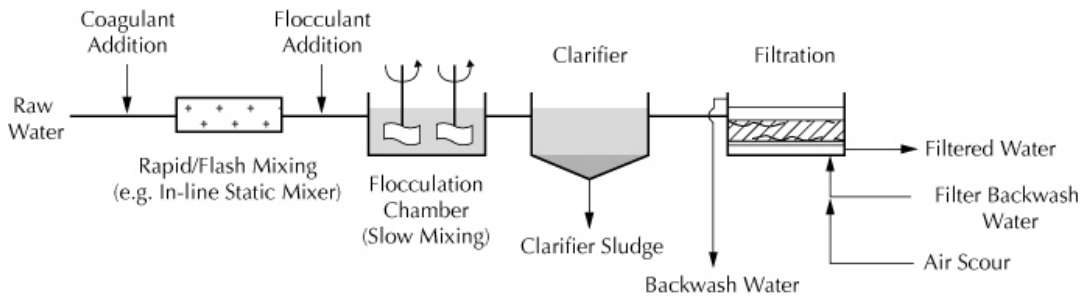
13.2 Coagulation process

Coagulation, flocculation and clarification, followed by rapid granular media filtration, are the key steps in conventional water treatment systems. This is a well-proven technology for the significant removal of colour and particulate matter including protozoa (eg, *Cryptosporidium* oocysts and *Giardia* cysts), viruses, bacteria, and other micro-organisms. Iron, manganese, tastes and odours may also be removed from the water by these processes.

If not removed, natural organic matter can react with chlorine to reduce disinfection efficiency and form chlorinated organic species, eg, disinfection by-products (DBPs), some of which are chemical determinands of health significance, see Chapter 10: Chemical Compliance and Chapter 15: Treatment Processes, Disinfection. Micro-organisms remaining in treated water may also pose risks to public health.

Conventional treatment (coagulation, sedimentation and sand filtration), as illustrated in Figure 13.1, has several distinct stages. A coagulant is added to neutralise the natural electrical charges on the colloidal particles that prevent them from agglomerating, and is rapidly mixed into the water to be treated. This process is referred to as the coagulation stage; it is sometimes referred to as the colloid destabilisation phase. The process water will then enter a flocculation chamber, where further chemicals may be added depending upon the raw water characteristics and the level and rate of treatment to be achieved. Gentle mixing during this stage allows particles to agglomerate and form settleable flocs.

Figure 13.1: Conventional coagulation, sedimentation and filtration

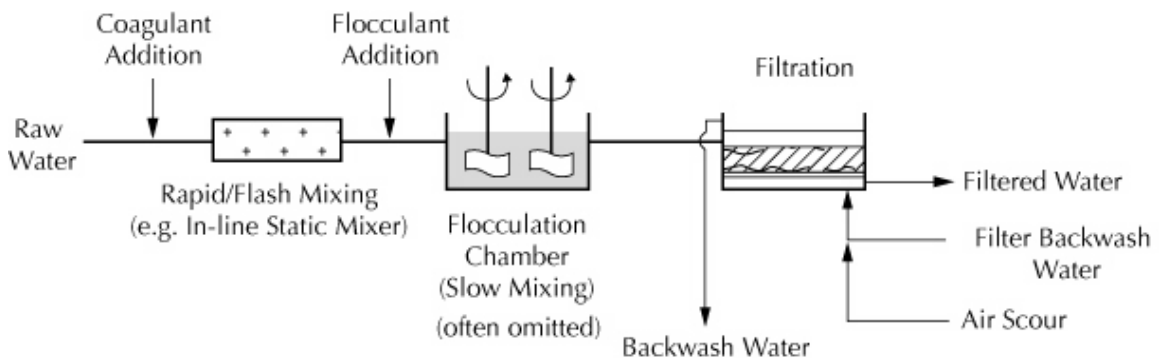


Clarification usually follows the flocculation process. Typically in New Zealand this involves sedimentation or settling, which allows the formed flocs to be separated for subsequent removal as sludge. Clarification is then followed by filtration which provides a second, polishing step for particulates that were not removed during the clarification step. The DWSNZ also cover the situation where rapid granular media filtration does not follow the sedimentation stage.

Some membrane filtration (MF) plants incorporate a coagulation and sedimentation step upstream of the MF step. The coagulation process may be continuous, or intermittent depending on the raw water quality.

For raw waters with consistently low colour (eg, less than 40 TCU) and low turbidity (eg, less than 10 NTU), direct filtration can be adopted, as illustrated in Figure 13.2. There is no clarification step in this case, and the coagulated water flows directly to the filtration process, providing the only particulate removal step. If the solids loading is too high, the filters will require frequent washing, which may lead to supply problems.

Figure 13.2: Direct filtration



As new clarification processes are emerging and becoming increasingly common, further variances from the conventional coagulation/filtration process may become more common. Lamella plates can be installed in place of traditional sedimentation tanks, and tube settlers can be placed in the tanks. These do not alter the basic principles of the process, but they may improve the efficiency, reliability, and allow higher throughputs for the same footprint to be achieved.

Dissolved air flotation (DAF) can be installed in place of the conventional sedimentation tank (or clarifier) and this process floats, rather than settles, the flocs. Widely used in Europe and now becoming more common in North America, DAF can be used for treating moderate turbidity and high colour waters. It is especially effective at removing algae, which can be difficult to remove by sedimentation and would otherwise clog downstream filters, and for raw waters that produce flocs with poor settling characteristics. The DAF process can be a good choice for very cold water temperatures because it is more effective at removing the weak flocs that are commonly produced in such waters.

A further development, the Actiflo® process, is a ballasted flocculation process, which adds microsand to the flocculation chamber. Coagulation, flocculation and clarification are provided as a single unit.

A further variation is the buoyant media clarifier (also called the adsorption clarifier). This process combines the flocculation and clarifier into one stage, and effectively acts more like a filtration process, rather than a settling clarifier. This process is best suited for raw waters of lower turbidity.

See WHO (2004a) for a description of coagulation systems, some operational aspects, and a discussion on their ability to remove various organisms. Refer also to Chapter 5 of the review draft LT2ESWTR Toolbox Guidance Manual (USEPA 2009) which discusses issues related to sedimentation.

The USEPA talks of 'enhanced coagulation' as though this were a new type of water treatment process. USEPA (2007) states that enhanced coagulation can include one or more of the following operational changes:

- increasing the coagulant dose
- changing the coagulant
- adjusting the pH (eg, using acid to lower the pH to as low as 5.5)
- improving mixing conditions or applying a moderate dosage of an oxidant
- adding a polymer.

Some advantages of enhanced coagulation are said to include:

- improving disinfection effectiveness
- reducing DBP formation
- reducing bromate formation
- enhancing arsenic and radionuclide removal.

Based on the above, 'enhanced coagulation' would seem to be little more than optimising the conventional process.

13.3 Coagulants and flocculants

13.3.1 Definitions

The addition of certain chemicals into the raw water causes particles to destabilise and allows agglomeration and floc formation to occur. The general terms for chemicals used for this purpose are:

- coagulants, which assist the destabilisation of particles (particularly colloidal sizes)
- flocculants (also known as flocculant aids or coagulant aids), which assist in the joining and enmeshing of the particles together. Most flocculants used today are polyelectrolytes.

13.3.2 Coagulants

Most New Zealand water treatment plants use aluminium-based coagulants (eg, aluminium sulphate (alum) or polyaluminium chloride (PACI – PACI is the preferred acronym because PAC can also mean powdered activated carbon). Aluminium chlorohydrate (ACH) has limited usage, mainly in membrane filtration. A very small number of plants use iron-based coagulants (ferric chloride or ferric sulphate). Although alum and PACI are most commonly used, other coagulants may have benefits in particular applications, such as low turbidity waters. NZWWA (1997, revised 2012) published the second edition of a standard that covered aluminium-based coagulants.

PACI and ACH are two of a number of pre-hydrolysed metal salt coagulant solutions that have been developed in recent years. The key characteristic of this class of coagulants is that they consume less alkalinity when added to the raw water, and are less affected by low water temperatures than alum.

In addition to aluminium and iron-based (inorganic) coagulants, organic chemicals known as polyelectrolytes may also be used as coagulants or flocculant aids, to assist in producing low turbidity levels in treated water. This is particularly necessary for high rate clarification and high rate filtration processes.

Polyelectrolyte coagulants such as polyamines, polyacrylamides, and polyDADMACs are used occasionally in New Zealand as the primary coagulant, especially on low turbidity, low colour waters, where treatment is by direct filtration. They can also be used in conjunction with inorganic coagulants, in which case they are referred to as coagulant aids or flocculants.

13.3.3 Flocculants

Polyelectrolytes are now commonly used as flocculants in the majority of water treatment plants in New Zealand. Used as a flocculant aid the polyelectrolyte is added following coagulant dosing to increase the size, strength and settleability of flocs. Polyacrylamide-based polyelectrolytes are the most commonly used flocculants in New Zealand. These may be cationic, anionic, or non-ionic. They are produced with varying degrees of ionicity and in a range of molecular weights. Generally, the higher the MW, the more effective the polyelectrolyte. Cationic polyelectrolytes usually perform better in New Zealand waters.

To achieve their full effectiveness, polyelectrolytes are added after the primary coagulant (eg, alum). A contact time of at least three minutes is not uncommon. Contact time in this context is the time the water takes to flow between the two dosage points.

13.3.4 Health effects

For some time concerns have been raised in the international technical literature and by interest groups about whether there are adverse health effects on consumers from residuals of chemicals in drinking-water following treatment. As an example, some communities have opted not to use aluminium-based coagulants because of unsubstantiated reports that claim that the aluminium in drinking-water poses a risk to public health, despite scientific evidence (eg, Srinivasan et al 1999) that adverse effects have not been demonstrated. Because there is no evidence of health risk, based on WHO (2004), the DWSNZ do not have a Maximum Acceptable Value (MAV) for aluminium. WHO (2012) does not change this point of view. These Guidelines include a datasheet for aluminium. Alternatives to aluminium coagulants exist, eg, iron-based coagulants such as ferric chloride, but there may be performance and cost penalties associated with their use.

Proven concerns do exist for kidney dialysis patients if the water that is used by the patient as the dialysate liquid contains high concentrations of residual aluminium. Users of dialysis machines should be advised to provide specific pre-dialysis treatment to ensure that residual concentrations of aluminium and some other contaminants potentially introduced by treatment chemicals and distribution materials are kept to acceptably low levels. This is absolutely critical if aluminium is being used in the treatment of a supply for the first time, even though DWSNZ are (strictly speaking) only applicable to water intended for drinking (refer section 1.3 of DWSNZ).

If water treatment chemicals are used in such a way that their residual concentration in the drinking-water does not exceed the MAV, available research indicates there will be no significant risk to health from drinking the water for a lifetime. However, industry practice is to operate treatment plants significantly below these levels.

Only flocculants that are specifically manufactured for potable water use should be used in drinking-water treatment. Many of the monomers used in the manufacture of polyelectrolytes, and their impurities and resultant degradation products, are toxic, and the manufacturing process needs to be controlled properly to limit the quantity of unreacted monomer in the manufactured polyelectrolyte. For example acrylamide (a monomer residual of the manufacture of polyacrylamides) has proven toxicity and carcinogenicity (its MAV is 0.0005 mg/L). Epichlorohydrin (present in dimethylamine/epichlorohydrin cationic polyelectrolytes) also has a MAV listed in the DWSNZ (0.0005 mg/L). The NZWWA Standards (1999, being revised 2012/13) for the supply of three types of polyelectrolytes for use in drinking-water treatment outline minimum requirements to ensure that high quality and low impurity products are used in drinking-water treatment applications.

Part 3.4 of the index section of the datasheets lists the chemical determinands with health (or possible health) concerns that can be found in water treated with coagulants and flocculants.

The total dose of polyelectrolytes applied in the water treatment process should be controlled to limit the residuals in the treated water, see Chapter 10: Chemical Compliance. In particular, the doses applied in sludge dewatering need to be taken into account if the supernatant water is recycled into the treatment process.

13.4 Coagulation and flocculation

13.4.1 Overview

Coagulation and flocculation processes are intended to form particles that are large enough to be separated and removed by subsequent sedimentation, or alternative clarification processes.

The coagulation stage occurs when a coagulant, such as alum, is added to the water to neutralise the charges on the colloidal particles in the raw water, thus bringing the particles closer together to allow a floc to begin to form. The coagulant solution should be applied at a concentration of around 0.5 percent, and certainly less than 1 percent (WHO 2001). Rapid, high-energy mixing (eg, mechanical mixers, in-line blenders, jet sparge mixing) is necessary to ensure the coagulant is fully mixed into the process flow to maximise its effectiveness. The coagulation process occurs very quickly, in a matter of fractions of a second. Poor mixing can result in a poorly developed floc.

The flocculation process which follows coagulation, allows smaller particles formed during the rapid coagulation stage to agglomerate into larger particles to form settleable and/or filterable floc particles. After coagulant addition, the process water is mixed slowly for a defined flocculation period, commonly 10–30 minutes, however the optimum flocculation time will vary depending on the raw water quality and downstream clarification process. Gentle mixing during this stage provides maximum particle contact for floc formation, whilst minimising turbulence and shear which may damage the flocs. Effectiveness of flocculation depends on the delay time (or contact

time) and mixing conditions prior to any flocculants being added, the rate of treatment, water temperature and the mixing conditions within the flocculation chamber.

Contact flocculation is a variation from conventional flocculation in which the flocculation takes place within the clarification process. The coagulation step remains the same, however the flocculation chamber contains a contact medium. This medium traps the flocculating particles, which will then attach to other particles, thereby continually increasing the size of the flocs until the build-up of particles clogs the media. Backwashing is then required to remove the flocculated particles. Refer to Figure 13.4 (upflow adsorption clarifier).

13.4.2 Jar testing

The best approach for determining the treatability of a water source and determining the optimum parameters (most effective coagulant, required dose rates, pH, flocculation times, most effective flocculant aids) is by use of a jar tester.

As optimum pH and coagulant dose vary significantly with raw water characteristics, an initial thorough investigation into the variations in raw water quality from the source should help in the selection of the appropriate type of coagulation system to be used and its design. Unexpected variations in raw water quality can cause the coagulation process to be compromised, causing consequent problems with treated water quality.

The normal procedure when conducting a jar test is initially to find the best performing coagulant and dose rate, and then to determine the optimum pH for the chosen coagulant and dose rate. Performance is usually judged on turbidity, and then on colour (or UV absorbance) removal. Jar tests can also be used to compare the usefulness of different flocculant polyelectrolytes, but not their optimum dose rates; this must be done on the plant itself.

Standard aluminium and iron salt coagulants are acidic and therefore neutralise the alkalinity present in the raw water. Excess alkalinity (after the addition of coagulant) is needed to allow good floc formation. The optimum coagulant dose added at the wrong pH could result in almost no floc formation. In New Zealand's soft surface waters the optimum pH for coagulation is often only achieved by adding an alkali such as soda ash (sodium carbonate) or hydrated lime, perhaps in the range of 5–20 mg/L, see section 13.4.3.

A raw water with a high pH and a low coagulant demand may not reach the optimal pH without adding acid. However, unless the acid requirement is quite high, the optimum pH is usually achieved simply by adding excess coagulant. This should not be done if it unduly increases the concentration of aluminium in the finished water.

Smaller water treatment plants often choose to use PACl to avoid the need to dose alkali or acid, as PACl is much less acidic than alum and is usually effective over a broader range of pH values.

To assist in maintaining good control of the coagulation process, jar tests should be carried out routinely as part of the plant process control. The procedure should be conducted frequently, whenever changes in the characteristics of the raw water occur, eg, after rain, intake changes, etc, or when the water treatment plant is performing poorly.

Depending on the experience of the operator and the extent to which the raw water characteristics have changed since the current dose rates were chosen, the first set of jar tests usually trials a range of coagulant doses. Examination of the results should indicate which coagulant dose is closer to that required for removal of the colour and turbidity.

Many water supplies need a second set of jar tests at different pH values, to give an indication of where the optimum pH is likely to be. Subsequent jar tests fine up on the dosage selection. Generally, the more turbidity and colour there is, the higher the optimum coagulant dose. Experienced operators will know, usually from the turbidity, how much coagulant is needed to remove the solids (or colour) load. Alum or iron salts are usually dosed at about 15–50 mg/L (solid weight equivalent).

The individual jars are assessed for a variety of factors, including which developed a floc first, which jar's floc grew the fastest and became the largest, which settled fastest and which gave a supernatant with the lowest colour, turbidity and coagulant residual. Normally, the same jar scores best on each count. In some difficult waters the optimum dosage conditions are different for colour and turbidity removal, or the optimum dose for colour and turbidity removal results in excessive residual concentrations of coagulant entering the distribution system. These waters require extensive jar testing to determine the best compromise. The number of jar tests needed to determine optimum parameters is learned from experience.

Refer to AWWA (2000) for further information on the jar testing procedure.

Additional laboratory equipment useful for managing coagulation and subsequent treatment includes a bench turbidimeter, colour comparator, pH meter, alkalinity titration equipment and a spectrophotometer for measuring aluminium and possibly iron and manganese residual concentrations following treatment. Colour measurement is a fairly subjective test, and readings made by a group of people can have a wide spread. If the laboratory intends to use a spectrophotometer, it may be wise to purchase a UV/visible model, because for a particular water a correlation can be established between the true colour (Hazen units) and the UV absorbance measured in a 1 cm cell at 254 or 270 nm after filtration. UV absorbance is able to be measured quickly and reliably.

13.4.3 Performance and control

The performance of coagulation and flocculation is dependent on a large number of factors, many of which are inter-related, making optimisation difficult. Source water characteristics, chemical dose rates, mixing conditions, flocculation times, the selection of chemicals and their order of addition, treatment rates, water temperature, can all affect performance. Control of pH and alkalinity is also essential to maintain performance.

Clarifier and filter performance will also be directly affected by the overall performance of these stages of the process. It is therefore critical to maintain good performance and control of coagulation and flocculation for overall treatment plant performance.

Depending on the pH of the source water, pH adjustment prior to coagulant addition may be required to achieve the optimum pH levels. Subsequent readjustment will almost certainly be required to ensure acceptable pH levels in the distribution system.

The optimum pH for the coagulation process varies with the choice of coagulant. For aluminium sulphate it is usually 5.5 to 7.5, for ferric salts it may be within the range 5 to 8.5. The optimum pH will vary with changing raw water characteristics.

Many surface waters in New Zealand have an alkalinity of less than 20 mg/L as CaCO₃. 1 mg/L of alum (measured as solid weight equivalent)¹ will consume 0.5 mg/L of alkalinity (as CaCO₃). If all the alkalinity is neutralised, no more floc will form. Often the alum dose that is required to coagulate all the turbidity and colour present requires soda ash, caustic soda or hydrated lime to be dosed to provide the additional alkalinity and maintain control of the pH. This commonly occurs after heavy rain, and if the alkalinity and pH are not controlled, process failure can result, with turbid water and dissolved aluminium entering the distribution system.

Being a sensitive, physico-chemical process, coagulation/flocculation is most reliable when raw water quality is consistent, when changes occur slowly, or when adequate automation is used to respond to changes in raw water quality. Unfortunately, this is not true of many of our streams and rivers. See Chapter 12: Pretreatment Processes, section 12.3.2 for a discussion on the benefits of off-river storage.

As raw water conditions change, optimal coagulation dose rates also change and careful control is required to prevent overdosing and underdosing.

Overdosing can lead to excessive concentrations of coagulant entering the distribution system, and waste money. This can occur if the pH and alkalinity are not controlled at optimum levels too. The guideline value for aluminium (an aesthetic determinand) is 0.1 mg/L as Al, which is approximately equivalent to 1.1 mg/L as solid weight equivalent alum.

¹ Solid weight equivalent alum refers to Al₂(SO₄)₃·14H₂O (molecular weight of 594). New Zealand liquid alum is delivered as 47% w/w (equivalent to 62% w/v). Sometimes alum doses are reported as Al₂O₃ (molecular weight of 102, 8.2% w/w of as-delivered liquid alum) or as Al (molecular weight of 54, 4.3% w/w of as-delivered liquid alum).

Underdosing can cause poor removal of colour, turbidity and micro-organisms.

Online monitoring of raw water quality determinands, such as pH and turbidity will aid treatment plant performance and assist in selecting optimum coagulation dose rates. It may be helpful to measure UV absorbance online if the raw water has high colour.

Severe rainstorms can seriously affect the quality of lake water, causing stress to the water treatment plant. With luck, the problem can be exacerbated by valve selection.

Water from the main tributary and side streams flowing into a lake or reservoir tends to find its way to water of the same specific gravity, which usually means water of the same temperature.

Rain falling during a cold southerly during the summer may be less than 10°C while the lake water may be about 20°C at the surface and 10°C at the bottom. This run-off will find its way to the bottom. Sometimes this can be observed visibly with the dirty flood water colouring the clean lake water – at the point where the flood water sinks there can be a distinctive plunge line. Until the lake water mixes, water from the upper valves remains relatively clean.

Flood water resulting from warm rain will remain on the surface, and until the particulate matter settles, water from lower valves may remain relatively clean for quite some time.

If the reservoir or lake is being aerated or circulated for manganese control the temperature will be much the same at all depths so the dirty run-off will tend to “blend” with the lake water, obviously assisted by the artificial mixing process.

Control of the coagulation process can be automated. Two control methods used in New Zealand for coagulation are the streaming current monitor (very common) and feed forward control (less common).

- Streaming current monitors measure the zeta potential (a measure of the electrical charge on the particles in the water) of the raw water following chemical addition and this can be used to adjust the coagulant dose rate accordingly as the raw water characteristics vary. This process was described by Ogilvie (1998).
- Feed forward control systems monitor natural organic matter (using UV light) and pH in the raw water prior to coagulant addition and predict the required coagulant dose rates to be applied.

13.5 Clarification and sedimentation

13.5.1 Overview

The term clarification, or sedimentation, is normally used to describe the settling of the flocs produced by the coagulation and flocculation process. This is distinct from presettling of highly turbid waters in detention ponds, which is discussed in Chapter 12: Pretreatment Processes, section 12.3.3.

Historically, clarification involved the simple principle of particle settling to separate the floc particles. New technologies such as dissolved air flotation (DAF), and high rate clarification processes, such as lamella plates, tube settlers, Actiflo[®], and buoyant media clarification, have been developed and are being used increasingly. These clarification processes are illustrated in Figures 13.3 to 13.6 and are described below. The majority of the clarifiers in New Zealand are of the upflow, sludge blanket, hopper bottomed configuration. However, there are small numbers of most other designs including horizontal flow, DAF, buoyant media clarifiers and lamella settlers.

The surface loading rate is a key parameter in clarifier design, irrespective of the clarifier type. This is usually expressed in $\text{m}^3/\text{m}^2/\text{h}$ (more correctly $\text{m}^3/\text{m}^2.\text{h}$ or m/h). This is the flow (m^3/h) that occurs over the horizontal area (m^2) of the settling zone of the tank. Acceptable surface loading rates vary significantly for the different clarification types from 2 m/h for a hopper bottomed upflow clarifier, to 12 m/h for a DAF process, to 40 m/h for the Actiflo[®] process.

Chapter 5 of the review draft LT2ESWTR Toolbox Guidance Manual (USEPA 2009) discusses various types of sedimentation basins.

13.5.2 Clarifier types

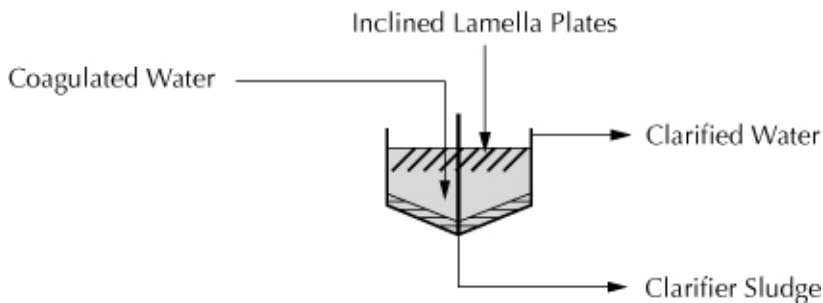
Conventional clarifiers

Conventional clarifiers (or sedimentation tanks) may be classified on the basis of flow direction (horizontal, radial, or upflow), the presence or absence of a sludge blanket, and shape (circular, rectangular, or hopper/wedge bottomed). A few earlier plants recycled a fraction of the sludge in an effort to enhance flocculation. Upflow clarifiers are suitable for a large range of raw water turbidities, however they are sensitive to flow changes. Flocculation times of 3–6 minutes are typical (further flocculation will continue to occur in the clarifier itself) whereas horizontal clarifiers require approximately 20–30 minutes flocculation time. Typical surface loading rates for conventional clarifiers are 2 m/h . This can be increased to up to 5 m/h if polyelectrolytes are used.

Lamella settlers

Lamella settlers, Figure 13.3, make use of inclined plates or tubes to increase the effective surface area for settling (and hence are also known as plate or tube settlers), thereby increasing the efficiency of the clarification process. For a given throughput the footprint of a lamella settler will be considerably less than a conventional clarifier. Typical surface loading rates are 5–15 m/h. Lamella settlers are less vulnerable to flow fluctuations than conventional clarifiers.

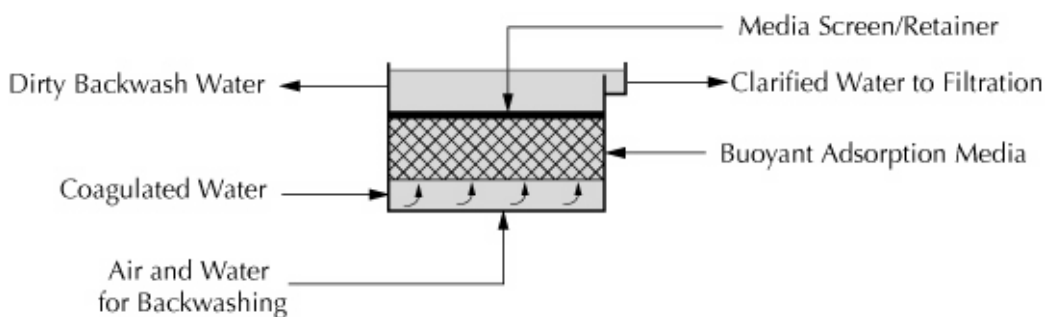
Figure 13.3: Lamella plates



Buoyant media clarifiers

Buoyant media clarifiers, or adsorption clarifiers, Figure 13.4, are a variant on the conventional clarification stage and combine flocculation and clarification into one step. The coagulated water passes through a medium of buoyant adsorption material (normally a plastic), kept in place by a screen. This allows contact flocculation to take place as flocs attach to the media and are thereby removed from the water. Solids will continually build up until the media clogs. Backwashing is then required to expand the media and remove the solids.

Figure 13.4: Adsorption clarifier



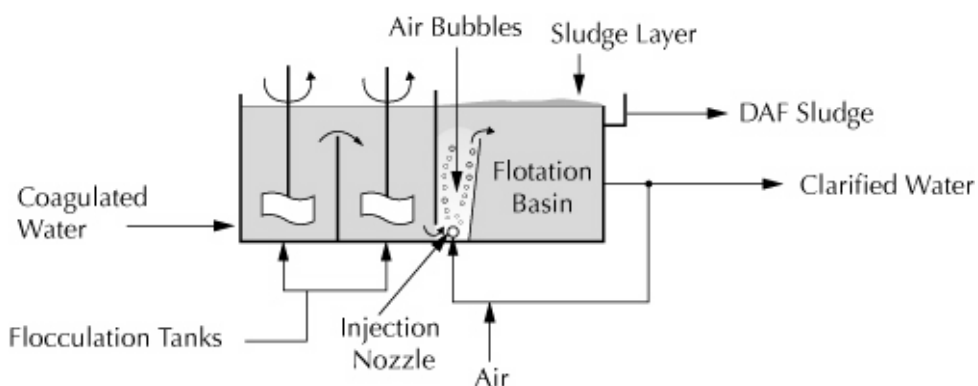
This process often requires a larger polyelectrolyte dose and is better suited to raw water sources with low turbidity and colour. High turbidities will very quickly clog the media and result in excessive backwashing. Typical surface loading rates of 19–25 m/h can be applied.

Dissolved air flotation

Dissolved air flotation (DAF), as illustrated in Figure 13.5, is a clarification process particularly effective for removal of colour, and algae cells that are difficult to settle. It is suited to moderate levels of turbidity, and only small doses of polyelectrolyte are typically required. Surface loading rates of 10–12 m/h are common.

The process works by injecting very small air bubbles near the inlet of the flotation tank, which attach to flocs (usually aluminium based) formed in a separate flocculation tank, and floats them to the surface. Flocculation times of 15–20 minutes are typically required. Clarified water is then collected from near the tank bottom. A portion of the flow (approximately 5–10 percent) is recycled and saturated with air. The recycled water re-enters the flotation tank through a series of nozzles, causing a pressure reduction that releases small air bubbles from the saturated water.

Figure 13.5: Dissolved air flotation (DAF)



Floated flocs collect as a sludge layer on the water surface. Periodic desludging occurs either by hydraulic flooding of the flotation tank, the sludge layer spilling over a collection weir, or by mechanical skimming, which will form a thicker sludge.

The in-filter DAF (sometimes referred to as DAFF) is a variation of the typical DAF process in which the base of the DAF tank is made into a rapid granular media filter, thus incorporating clarification and filtration into one step.

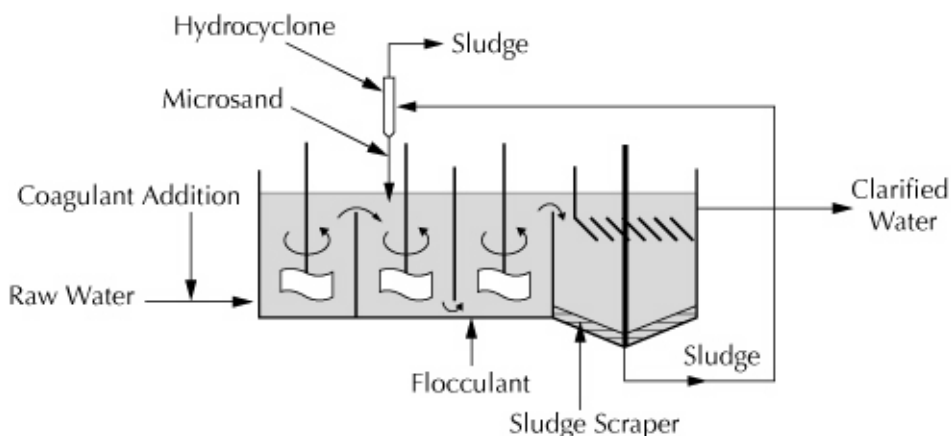
Pulsed blanket clarifiers

Pulsed blanket clarifiers use a vacuum system to create pulsations to hold the sludge blanket in suspension and aid flocculation, allowing for higher surface loading rates (up to 3 m/h). In the Superpulsator® system (installed at the Waikato Water Treatment Plant), clarification is enhanced by inclined plates, allowing surface loading rates of up to about 6 m/h.

Actiflo

The Actiflo® process is a package plant, microsand ballasted clarification process, as illustrated in Figure 13.6. The process reduces flocculation times to approximately 5–10 minutes, and allows very high surface loading rates of 30–40 m/h (up to 100 m/h). There are no Actiflo® units operating in New Zealand as at 2005.

Figure 13.6: Actiflo process



Coagulant addition and mixing occurs in the first chamber. Polyelectrolytes and microsand are added in a second chamber, and flocculation occurs in the third chamber. The flocculated water is then passed through a lamella settler. Settled sludge is collected and passed through a hydrocyclone, in which the microsand and floc particles are separated. The microsand is recycled back through the process and the sludge is separated for disposal.

The use of microsand as a seed for floc formation improves performance in two ways. The high specific area assists floc formation, whilst the high specific density improves the settleability characteristics of the flocs.

The Actiflo® process is similar in some respects to the Sirofloc process that was developed in Australia in the 1980s, except that the Sirofloc process uses 1–10 µm magnetite that behaves similarly to a coagulant when added (with acid) to the raw water. The resulting suspension is then subject to a magnetic field to form settleable flocs. The magnetite is recovered and reused.

13.5.3 Optimisation and performance issues

Most clarifiers will provide a reasonable level of treatment provided the upstream chemical dosing is optimised, and a reasonable surface loading rate suitable for the clarification type, is not exceeded. For example, studies on the removal of protozoal cysts in conventional treatment have shown that the clarifier is usually responsible for over 90 percent (1 log) of the (oo)cyst removal (USEPA 2003).

High effluent turbidities in water leaving a clarifier are indicative of poor performance. Flocs, which should have been removed in the clarifier, pass out and on to the filters. This will result in reduced filter run times and poorer filtered water quality. A well-operating clarifier should be able to produce an effluent of turbidity 2 NTU or less. Conventional clarifiers are sensitive to changes in flowrate, however, high rate clarification processes are less susceptible to such changes.

There is limited guidance for clarifier performance. The US Partnership for Safe Water Guidelines for Phase IV *Excellence in Water Treatment* sets performance goals as part of overall plant performance to achieve less than 0.10 NTU filtered water. This includes clarified water turbidity:

- less than 1.0 NTU 95 percent of the time when raw water is less than or equal to 10 NTU
- less than 2.0 NTU 95 percent of the time when raw water turbidity is >10 NTU.

Despite this, it has often been found that the sedimentation process is more effective when the raw water is turbid; some earlier plants with low turbidity raw water took advantage of this by dosing bentonite into the raw water.

The rate at which particles settle is dependent on water temperature, or more accurately, water viscosity. In summer when the water temperature is perhaps 20°C, particles may settle up to 50% faster than in winter, when the water temperature is perhaps 10°C, however, most water treatment plants operate at a lower rate during winter.

A key aspect of consistently achieving <0.10 NTU filtered water turbidity is that changes in raw water turbidity should have minimal effect on clarified water turbidity, and negligible effect on individual filter turbidity. This requires optimisation of coagulation.

A common operational problem in clarifiers of the hopper-bottomed upflow type in New Zealand is for short-circuiting currents to occur, usually in summer and around the middle of the afternoon. This can be attributed to a temperature differential between the incoming water and the water in the tank. The result is a billowing of the floc blanket and subsequent carry-over of floc on to the filters. The same effect can be caused by algae in the sludge blanket becoming buoyant due to increased production of oxygen due to photosynthesis. High algal populations are needed for this effect to become a nuisance. Clarifiers with good inflow mixing do not seem to experience the same degree of problem. The only satisfactory solution to this problem, (apart from fitting tube settlers to the tank), appears to be to reduce the flow and hence the surface loading rate during the problem period.

Another common problem is excessive floc carry-over caused by uneven flows occurring over the clarifier surface. Inspecting and levelling the outlet weirs to ensure that all receive equal flows can correct this. If the flows are still uneven, the inlet flows to each clarifier must be checked, and adjusted so that they are even. For non-hopper bottomed clarifiers it is also important to ensure that the distribution of the flow within the clarifier is even.

Multiple tanks in larger plants often experience a high frequency wave in the outlet weirs that may disrupt the floc blanket. However, this generally does not cause a significant problem.

For clarifiers using a floc blanket, good control of the blanket surface and regular removal of floc from both the top and body of the blanket and base of the tank is important. In conventional clarifiers, the use of sludge (or gravilectric) cones gives better results than the earlier system of constructed corner pockets. Bottom sludge scours should be operated regularly (based on experience) to keep sludge fresh and to prevent excessive sludge build up. Bottom sludge has been known to go anaerobic at plants with a high level of organic matter or algae in the raw water.

Regular sludge removal is important for all clarifier types. For DAF units, desludging should also occur regularly to prevent sludge re-settling. The sludge in this process is exposed, so it is important that the tanks are covered to prevent the rain and wind affecting performance.

Buoyant media clarifiers need to be backwashed when the media becomes clogged, again to prevent excessive floc carry-over to the downstream filtration step.

Growth of algae and slimes on the walls of sedimentation tanks and other channels should be discouraged. Regular cleaning is recommended, because such material can increase the levels of dissolved organic matter that the plant must contend with, and can contribute to taste and odour problems.

13.6 Lime softening and ion exchange

Water containing significant concentrations of calcium and magnesium is referred to as hard water. Hard water can cause scaling of pipes and household appliances and reduces the solubility of soaps and detergents in the water.

Lime softening and ion exchange processes can be used to soften water, however both are currently of limited use in New Zealand for drinking-water, mainly because, on average, New Zealand waters are softer than those found in many other parts of the world.

13.6.1 Lime softening

The lime softening process removes hardness by chemical precipitation, followed by sedimentation and filtration, therefore showing similarities to the conventional chemical clarification process. Lime, caustic soda (sodium hydroxide) or soda ash is added to the water, increasing the pH, which causes the metal ions to flocculate and precipitate. The metal precipitates are removed during the sedimentation stage, prior

to filtration. Other contaminants may also combine with the precipitates and be removed by this process.

Calcium concentrations can be reduced at pH 9.5 to 10.5 in lime softening processes, although magnesium requires pH 10.5 to 11.5. Several organisms are inactivated at the latter pH; see WHO (2004a) for further information. The microbial treatment mechanism of this process is a combination of inactivation due to elevated pH levels, and removal by sedimentation. However, *Cryptosporidium* and *Giardia* are not inactivated by high pH levels. Removal of protozoa through this process is solely due to the sedimentation and subsequent filtration. Section 5.4 of the DWSNZ specifies the compliance criteria that need to be satisfied in order to qualify for 3 log credits.

A single stage lime softening plant consists of a primary clarifier and filtration step. An additional clarifier is required between the primary clarifier and the filtration step for two-stage lime softening. A coagulant is added to both stages of clarification. Two-stage lime softening can provide additional *Cryptosporidium* removal due to the additional sedimentation stage within the process. Refer also to Chapter 6 of the review draft LT2ESWTR Toolbox Guidance Manual (USEPA 2009) which discusses issues related to lime softening.

13.6.2 Ion exchange

Ion exchange is discussed in this section because it is used frequently to soften water; it is not a coagulation process, and does not earn protozoal log credits. Many aspects of ion exchange are covered in NSF/ANSI 44-2004.

Ion exchange treatment units can be cationic, anionic, weakly or strongly ionic, or mixed bed, depending on the reason for its use.

Mixed bed units are employed for producing deionised water, usually for laboratories and industry. WHO (2005) also discusses some negative aspects of drinking deionised, distilled or reverse osmosis water, due to their tastelessness, and loss of essential minerals, mainly calcium and magnesium. This is discussed briefly in Chapter 10: Chemical Compliance, section 10.2.2.

Cationic beds can be used to remove calcium from the water, usually replacing it with sodium; if iron and manganese exist in the water in the soluble state (ie, ionic) their concentrations can be reduced as well. The process needs to be monitored to determine when the resin needs recharging. Some smaller units use a colour indicator for this purpose.

Strong-base anion exchange can be used to reduce the concentration of arsenic in the form of soluble arsenite or arsenate. This process replaces most anions in the water, usually with chloride ions, which can make the water corrosive.

There are currently two approaches to nitrate removal. One is as described in the previous paragraph, where all anions are replaced with chloride. Since anion exchange resins are generally more selective for sulphate over nitrate, the capacity of a resin for nitrate removal will be limited by the concentration of sulphate. The other approach is to use a nitrate selective resin, usually reducing nitrate to less than 2 mg/L as N.

WHO (2004a) describes ion exchange as follows:

Ion exchange is a treatment process in which a solid phase presaturant ion is exchanged for an unwanted ion in the untreated water. The process is used for water softening (removal of calcium and magnesium), removal of some radionuclides (eg, radium and barium) and removal of various other contaminants (eg, nitrate, arsenate, chromate, selenate and dissolved organic carbon). The effectiveness of the process depends on the background water quality, and the levels of other competing ions and total dissolved solids. Although some ion exchange systems can be effective for adsorbing viruses and bacteria, such systems are not generally considered a microbial treatment barrier, because the organisms can be released from the resin by competing ions and flow changes. Also, ion exchange resins may become colonised by bacteria, which can then contaminate treated effluents. Backflushing and other rinsing procedures, even regeneration, will not remove all of the attached microbes. Impregnation of the resin with silver suppresses bacterial growth initially, but eventually a silver-tolerant population develops. Disinfection of ion exchange resins using 0.01 percent peracetic acid (one-hour contact time) has been suggested.

As explained in the previous paragraph, ion exchange cannot be relied upon to consistently remove (oo)cysts from water, hence does not qualify for protozoal log credits. Ion exchange resins have been developed that can reduce the concentration of natural organic matter, eg, as used in Orica's (now IXOM's) MIEX (magnetised anion exchange resin) process. The MIEX[®] Process uses a fluidised bed ion exchange reactor to remove dissolved organic carbon. This process can be used upstream of a conventional chemical coagulation plant that has difficulty in complying with the criteria in section 5.4 of the DWSNZ. Although this ion exchange process does not qualify for log credits on its own, it may well be possible for the whole process to earn 3 log credits (section 5.4), or 3.5 (section 5.4 plus 5.7), or even 4 log credits (section 5.4 plus 5.8). The use of ion exchange resins that reduce the concentration of natural organic matter may offer the additional advantage of reducing the concentration of disinfection by-product precursors sufficiently to avoid monitoring for, or removing, DBPs. MIEX may also reduce the natural organic matter sufficiently from water with a low UVT (high UV absorbance) to render UV disinfection economic.

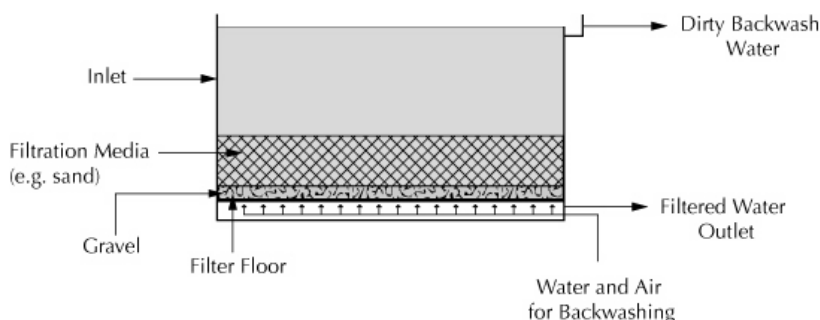
Ion exchange is discussed in Chapter 9 of AWWA (1990).

13.7 Rapid granular media filtration

13.7.1 Overview

Rapid granular media filtration, as illustrated in Figure 13.7, provides the conventional polishing step following coagulation and sedimentation, and is the only floc removal/polishing step in direct filtration plants. It is the most common type of filtration used in New Zealand water treatment plants. The filter may operate by gravity or pressure. Other filtration processes not generally used in conjunction with coagulation are discussed separately in Chapter 14: Treatment Processes, Filtration. WHO (2004a) discusses some design, operation and performance aspects of granular media filtration. Refer also to Chapter 7 of the review draft LT2ESWTR Toolbox Guidance Manual (USEPA 2009) which discusses issues related to filtration, including enhanced individual and combined filtration.

Figure 13.7: Rapid granular media filter



Like clarifiers, filters can be described by their treatment rate. This is usually expressed as $\text{m}^3/\text{m}^2/\text{h}$ (more correctly $\text{m}^3/\text{m}^2\cdot\text{h}$ or m/h) and is the flowrate (m^3/h) that occurs over the surface area (m^2) of the filter bed. Filtration rates are also measured as mm/s .

Older filters were designed to operate at around 5 m/h (1.4 mm/s). However, many modern filters and dual media filters will operate at higher filtration rates of 10–15 m/h (2.8–4.2 mm/s), especially if the coagulant is assisted with polyelectrolyte.

As water passes through a filter bed of media, particulate matter (including micro-organisms) is trapped within the media primarily by a two-step process in which particles are moved to the surfaces of media grains or previously captured floc, and then become attached (adsorbed) to these surfaces. Physical straining is only a minor factor in rapid granular filtration.

The particles that build up in the bed are subsequently removed by backwashing at regular intervals. Traditionally, single medium sand filters of shallow depth (typically between 600 and 750 mm excluding the support gravel) were the most common. However, newer plants often contain dual media, either anthracite or thermally modified pumice (silicon sponge) over sand, or coarse medium deep bed with typical total media depths of between 1.2 and 1.5 m. For further information on these newer media refer to Kawamura (2000), and for pumice (or porous ceramic dual media) filters refer to Hill and Langdon (1991).

The concept of dual or multimedia filters is to include a relatively coarse medium (eg, anthracite) on the top, followed by finer media beneath. This causes deeper penetration of the particles being removed, allowing longer filter runs. Some multimedia filters use a very fine medium at the bottom of the bed (eg, garnet); this allows finer particles to be trapped but increases the headloss. The effectiveness of multimedia filters depends on the media remaining separate even after multiple backwashes. This is achieved by a balance between the relative densities of each filter medium and the backwashing conditions. Depending on the nature of the particles being removed, multimedia filters may be effective without using coagulation.

By using a polyelectrolyte as a coagulant aid or filter aid, the strength or 'stickiness' of the attachment between the floc particles and the media grains is increased, allowing higher filtration rates and coarser media gradings to be used thereby reducing the rate that headloss increases. It also means the filter is less likely to let go of these particles following flow increases or surges.

If too much polyelectrolyte is dosed, the particles will adsorb to sand grains at the top of the filter, causing the headloss to increase too quickly; excessive polyelectrolyte dosage may also cause backwash problems. At a more appropriate polyelectrolyte dose, the particles penetrate further into the bed, making more use of the full depth of the media, and allowing much longer filter runs. If the polyelectrolyte dose is too low, many of the particles may pass through the bed if the filter grains are coarse or the filtration rate too high. Bed penetration can be assessed by measuring the headloss at various depths through the filter.

Before the introduction of polyelectrolytes, filter sand was usually in the 0.6 to 1.2 mm diameter range, that is, in the 14/25 sieve range. Using such fine sand was considered necessary to strain out the particles. Using polyelectrolytes enables use of coarser sand, such as in the 2 to 4 mm range. The advantages include less headloss, and deeper penetration thereby using more of the bed leading to longer filter runs.

Rapid granular filters can be operated at either a constant rate of flow (constant rate filtration) or at a flow rate that declines as headloss builds up during a filter run (declining rate filtration). Constant rate filtration is the more common method and is normally achieved by the control valve on the filter outlet opening progressively during a filter run to compensate for the build-up of headloss through the bed.

Water treatment plants may not be able to remove all the soluble manganese. One technique that is used to enhance manganese removal is to use greensand filters; apparently with varying degrees of success. ANSI/AWWA Standard B102-10 is titled Manganese Greensand for Filters.

Backwashing is the term used to describe the cleaning of the filter by passing water (often preceded by, and/or in combination with, air) in the reverse flow direction to when the filter is in normal operation. Similarly to the term filtration rate, the term backwash rate in m/h (or mm/s) is used to describe the intensity of the backwash operation. Traditionally in New Zealand, backwash rates were low (typically 20–25 m/h), preceded by an air scour at a similar rate. There are a variety of systems in use including air scour followed by water backwash, water only, and combined air/water followed by water backwash. Modern best practice is a combined air scour/low rate water backwash (the optimal regime is known as collapse pulsing), followed by a high

rate water backwash (as high as 55 m/h). A bed expansion of 20 percent is the objective during the high-rate backwash to ensure full bed fluidisation and adequate cleaning. Note that to achieve the same degree of bed expansion will require higher flow rates in summer compared with winter, as warmer water has a lower viscosity than cold, and the effects of this should be considered in backwash design.

13.7.2 Turbidity monitoring

Turbidity measurement is used to assess the efficiency of the filter in achieving protozoa removal for compliance with DWSNZ. Sampling must be made on water directly from the filtration process. The DWSNZ require turbidity monitoring of each filter (unless the population served is below a threshold value – see Table 5.3 of DWSNZ). Particle counters can also be used to measure and optimise filter performance, but these are not required for compliance purposes.

Although turbidimeters are not required on individual filters at smaller plants, their use is strongly encouraged. This is because when measuring a combined effluent from multiple filters, one filter may be producing poor quality water that is then diluted by good quality water from the other filters and the sub-standard filter's performance would not be noticed. Continuously monitoring each filter will indicate whether any slow start mechanism, filter-to-waste, the headloss control, filter run length, filtration rate control, and filter cleaning are operating or selected correctly.

To earn 3 log credits under DWSNZ for protozoa removal using the coagulation, sedimentation, filtration process, or 2.5 log credits for direct filtration, one of the requirements is that the filtrate from each filter must be less than 0.30 NTU for at least 95 percent of the time (DWSNZ, sections 5.4 and 5.5).

Additional log credits are available for enhanced filtration, ie, individual filter effluent (IFE) monitoring and combined filter effluent (CFE) monitoring, see Chapter 8: Protozoa Compliance. These will usually be the standard rapid granular media filters, but producing a lower turbidity filtrate. The standard tungsten lamp type nephelometer may not be sensitive enough at such low NTUs; a laser turbidimeter may be required. Turbidity measurement and calibration is discussed in Chapter 8: Protozoa Compliance, section 8.6.2.

13.7.3 Filter operation

As solids build up through the bed, headloss across the bed will increase and at some stage filtrate turbidity will also increase. Backwashing frequency can therefore be triggered by headloss, turbidity or filter run times (based on operational experience). The filter goes through a ripening period when it is brought back online, during which time the filtrate quality will be substandard. For this reason slow-start, delayed starts, and filter-to-waste are becoming common practice.

13.7.4 Optimisation of the filtration process

Increased filtrate turbidity (or residual coagulant, eg, aluminium or iron) is the primary indication of problems with a filter, however reduced run times (caused by turbidity or headloss reaching the set point earlier than usual) can also highlight problems.

Raw water that has high colour and low turbidity (and typically with low alkalinity) can be very difficult to treat, particularly when the water is less than say 10°C. The floc often only forms in a narrow range of alum dose and pH conditions. It is usually small, slow to form, and light, so that it is very susceptible to shear due to flow changes. It can even be difficult to see. Removal of protozoa in these conditions will be sub-optimal. These waters can also result in elevated aluminium levels in the filtered water, and hence additional attention should be paid to monitoring filtered water aluminium.

If filtrate turbidity increases are observed across all the filters, there is likely to be a common problem upstream of the filters. The following are some possible causes of high turbidity in the filtered water:

- non-optimal coagulant dosing may cause poor floc formation, which can overload and/or pass through the filters; this can be caused by selection of an inappropriate alum dose, raw water alkalinity too low for the alum dose rate being used, or coagulation occurring at the wrong pH
- operational problems such as the alum solution being the wrong strength (or even run out!), or the automatic adjustment to flow rate being faulty, or inadequate sludge removal from the settling tanks
- dose pumps not performing to specification; a good practice is to check the pump discharge against the dose setting (sometimes called the stroke), for example, by using dose timers, or calculating from the weight used while a measured flow has been treated
- flowrates may have been increased too rapidly, causing sludge blanket instability
- floc carry-over from a poor clarification process will increase the solids loading on to the filters, reducing run times and causing excessive backwashing
- insufficient polyelectrolyte for the conditions, causing sludge blanket instability
- excessive polyelectrolyte dosing, which can quickly blind the filter and reduce filter runs, thereby causing the filtered water turbidity to increase earlier than expected
- flow increasing excessively through the remaining filters when one is being washed
- direct filtration, being a one-step process, is particularly susceptible to sudden changes in raw water quality and flowrate.

If filtered water turbidity is high on a single filter, the problem is likely to reside only with that filter. Some problems, their consequences, and potential indicators are listed below:

- backwash/air scour flowrates too low resulting in a partially washed filter being put back into service
- backwash/air scour flowrates too high resulting in loss of sand, allowing particles to pass through the shallower bed

- insufficient duration of washing, also resulting in a partially washed filter being put back into service; an elevated clean bed headloss (above normal values) on start-up immediately after a backwash is a good indication that insufficient backwashing has occurred
- failed or blocked backwash nozzles or underdrain system. This situation results in excessive filtration rates and backwash flows through that part of the filter bed that is still in operation. Observing a filter during a wash can assist in detecting individual failed nozzles: the overall water or air distribution pattern during the wash will be uneven
- filter flow meter, controller, or filtration rate indicator may be out of calibration
- uneven flow split to each filter may cause reduced filter run times for some filters and excessive flows to others. Inlet pipe or channel configurations should be checked.

If filter runs are longer than expected, they may not be due to improved quality of the water feeding the filters. They can result from:

- backwash/air scour flow rates being too high or the duration too long. Over-washing may lead to media loss (thus reducing media depth in the filter), or impairment of the media's ability to adsorb particles. Checking and recording the media depth at regular intervals can highlight if media is being lost due to over washing
- if the alum dose is incorrect, or raw water alkalinity too low for the alum dose rate being used, minimal floc may be forming, reducing the solids loading on the filter, thereby increasing filter run times. Protozoa removal will be sub-optimal
- polyelectrolyte dosage is important, particularly in high rate or coarse-grained filters. As mentioned above, too much polyelectrolyte can blind the filter, but too little polyelectrolyte can result in some floc passing through the bed
- plants treating raw water with a low turbidity and average to high natural organic matter, often using direct filtration, may produce filtered water with a low turbidity despite very little of the aluminium being removed. A slower than usual increase in headloss indicates a low removal rate of particulate matter. Plants treating raw water like that should test for aluminium in the final water to check that the process is operating satisfactorily.

Sudden flow changes can cause problems with filtrate quality, eg, when:

- filters are taken out of service, as there will be a corresponding flow increase to the other filters. Allowing only gradual flow changes during this operation, rather than a sudden change, will minimise these effects
- poor flow control at the outlet from the filter typically caused by incorrect valve and/or actuator selection
- inadequate storage of treated water can require sudden increases in flow through the plant which will challenge the whole treatment process.

Monitoring the raw water quality, optimisation of the coagulation and clarification processes, and good operating procedures can minimise these effects.

Other common problems with granular media filters include bed cracking, shrinkage of the media away from the walls, mudballing, and the media in multimedia beds intermixing. These are generally caused by excessive clarifier effluent turbidity, dosing polyelectrolyte too high, poor filter backwash/air scour capability, or excessive filtration rates for the filter type, and can usually be checked by visually assessing or sampling the media.

Mudballing problems (ie, sand particles sticking together) can be alleviated by using high pressure sparge cleaning and/or acid, chlorine or caustic soda washing to break up the mud balls. Often there is a more fundamental problem that needs to be addressed to solve the problem long term, such as inadequate filter backwashing that may require significant upgrading of the filters.

A quick checklist that can be used if the turbidity of a filter effluent exceeds the required or normal level is as follows; determine whether:

- the raw water quality changed
- the solids loading on the filters increased
- the coagulant dose was selected correctly
- the coagulant is being dosed correctly
- the coagulation pH is optimum
- all the alkalinity has been neutralised
- polyelectrolyte is needed or is being dosed correctly
- the turbidity excursions occur at the same time of day or season (eg, algal problems)
- one or more of the filters is responsible
- the filter-to-waste period should be extended
- the filters are receiving unequal flows
- the backwash and air scour flows and pressures are correct
- parts of the bed are mudballed (blocked), causing uneven filtration rates
- the filter beds are cracked or shrinking away from the walls
- excessive sand loss has reduced the media depth
- the filter rate is excessive for the type of filter
- the problem only occurs when 'a certain' operator is on duty.

If the filtered water turbidity readings tend to produce spikes, check whether:

- all filters are responsible
- the filters are returning to service too soon after a wash
- the slow start mechanism is operating correctly
- a filter run was excessive
- the state of the filter bed and underdrainage system cause poor backwashing
- the headloss instruments or flow controllers are inaccurate
- the treatment plant output increased too much or too rapidly

- the flow balancing system is operating correctly (eg, when a filter is taken out of service for washing)
- the filter outlet valve is modulating smoothly enough
- more polyelectrolyte is needed to cope with short periods of high flow
- it happens at the same time as something else (eg, when pump settings or valves are altered or when the washwater is returned).

For further reading, try USEPA (1999). Section 4.2 deals with system evaluation and plant optimisation, section 5 deals with individual filter self-assessment, and section 6 with comprehensive performance evaluation.

WHO (2001) covers a lot of ground too.

13.8 Second stage filtration

Secondary filtration is a process whereby an entirely separate rapid granular filter box or vessel is used as a second filtration stage following a first stage filter (ie, two separate filters used in series).

To qualify for additional log credits, coagulation must have taken place before the first stage filter, which may contain a coarse medium, followed by the secondary filtration stage that is typically a conventional dual or multimedia filter. Additional coagulants (or more commonly) filter aids (polyelectrolytes), or oxidants can be added between the first and second stages.

Some reasons for using two-stage filtration include:

- following direct filtration if the raw water quality is variable and the option is cheaper than building sedimentation tanks
- where the treatment plant occasionally experiences periods of stress, eg:
 - when very cold winter water causes aluminium flocs to form slowly
 - or during high summer flows
- to remove iron and manganese after an oxidation stage, eg, after chlorination
- to remove grit from poor quality lime. At this elevated pH, more iron and manganese may be removed too
- to remove further organic matter, including any disinfection by-products, by using granular activated carbon (GAC) filters or biologically activated carbon (BAC) filters.

Complying with section 5.4: Coagulation, sedimentation and filtration processes earns 3 log credits. Complying with section 5.5: Coagulation, direct filtration: treatment earns 2.5 log credits. Secondary filtration may earn an additional 0.5 log credit for protozoal compliance, refer DWSNZ, section 5.6.

The secondary stage filters must involve the use of a rapid sand, dual media, granular activated carbon (GAC or BAC), or other fine grain media unit process applied in a separate stage following rapid granular or dual media filtration. To qualify, a continuous chemical coagulation process must be in operation upstream of the first filters. One of the monitoring requirements is that the turbidity of the water leaving the secondary filters must not exceed 0.15 NTU for more than 5 percent of the time, see section 5.6.1 of the DWSNZ. See also USEPA (2003), and Chapter 9 of the review draft LT2ESWTR Toolbox Guidance Manual (USEPA 2009) which discusses issues related to second stage filtration.

Sometimes the coagulation process is followed by membrane filtration. In this situation, a second stage filter cannot earn additional log credits. The main reason is that water that has passed through a very fine filter should not earn any more log credits for passing through a much coarser filter. A compliant membrane filter will already be producing water with a turbidity less than 0.10 NTU, so it is not logical to earn more log credits for producing water that could have a higher turbidity!

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