# Water Treatment

## 2.1 Chapter Overview

The following sections are a brief introduction to drinking water quality and treatment, with a particular emphasis on the conventional treatment processes of coagulation, flocculation and clarification, which are most relevant to this thesis.

A brief overview of a typical conventional drinking water treatment plant is given, then a description of the particles to be removed, types of contaminants to be removed, and how this is normally measured. The coagulation, flocculation and clarification processes are covered next in more detail, and then the traditional methods of determining coagulant dosage, jar tests and streaming current control, are introduced.

Space precludes a thorough treatment of drinking water treatment, which is an area that uses a variety of technologies and has a long history, while still being a subject of much active research. This background focuses almost exclusively on aspects of the treatment process relevant to this thesis.

More information on material in this chapter can be found in literature on drinking water quality and treatment. Some standard texts include [AWWA 1990 pp 269-284], [AWWA and ASCE 1998 pp 87-110] and [Green TEXT book], while [Zeta-Meter 1993] and [Bratby 1980] focus more on coagulation and flocculation.

# 2.2 Conventional Drinking Water Treatment

Ideally, raw water sources for drinking water treatment plants are chosen to be extremely clean and free of contamination. This is true for many underground sources, which require little treatment. However only surface water from lakes or rivers is available to supply most population centres, this water normally requires significant treatment to be suitable for consumption.

Water is typically drawn through a screen, or trash rack, to remove other large debris from the river or reservoir. Ideally the next step is pre-sedimentation to remove sand, silt and other gritty material that will settle out easily, but which may be present after storms or heavy rains that stir up the water. A step that sometimes follows is microstraining. This is normally a very fine screen for the removal of large algae and other aquatic organisms, which would otherwise tend to clog the filters. These initial steps are often not be present or required, depending on the source. They remove only the largest of impurities from the water. Those that remain are called 'non-settleable' solids and require chemical treatment.



Figure 2.1. Overview of a conventional treatment plant.

The next steps of the process are what is referred to as 'conventional treatment'. This is by far the most common treatment for surface water. An overview of a conventional plant is shown in figure 1.

The first stage is coagulation, the adding and rapid mixing of chemicals to water, in order to destabilise the suspended particles. Then comes flocculation, this is the slow mixing of the coagulated water to assist in the build-up of larger particles, called floc, from the newly destabilised smaller particles. Sometimes a chemical called a flocculant aid is added to assist with this.

Next is clarification, where the water flows slowly upwards or across large settling basins (called clarifiers) that allow the floc to settle. A large majority of the suspended material remains in the clarifiers, while the water is drawn off from the top. These three processes are covered in more detail later in this chapter in sections (xx and xx).

Filters remove any remaining suspended particles. Sand filtration is the most commonly used, where the water is passed through layers of sand. Particles are removed both by mechanical straining where they become lodged in the media, and by adsorption where the particles stick to the surface of the media. Modern rapid sand filters have a number of different types of media of different coarseness, they can be pressurised for higher flow rates, although use of gravity is most common. Filters require periodic cleaning to remove the trapped dirt; this is done by back washing. If the water going to the filters has too much dirt, it will result in blockage, reduced flow or particles breaking through. There is a lot of science to optimal filter design and operation, which will not be discussed here.

Disinfection is typically the final stage to destroy any remaining harmful microorganisms. The most common disinfectant is Chlorine, although other chemicals can be used. The disinfectant chemical must be dosed in sufficient quantity to deactivate all dangerous micro organisms before the water reaches the first consumer. Another approach that is growing in popularity is the use of intense ultraviolet (UV) light to disinfect the water. Whatever the method of disinfection, it can only be effective if the water is already very clean.

Each major stage may be accompanied by additional chemical dosing to provide the best operation. Examples are as pH correction before coagulation, the addition of some disinfectant before clarification to inhibit algae or pH correction before Chlorination.

The final water may also have chemicals added to benefit public health (such as fluoride) or to reduce corrosion in water mains.

## 2.3 Turbidity, Particles and Micro organisms

#### 2.3.1 Turbidity Particles

The non-settleable solids can consist of a combination of bacteria, viruses, protozoa, and other biological organisms as well as suspended or dissolved organic compounds and large amounts of inorganic matter of various types. The term applied to all suspended matter is turbidity.

The reason that the non-settleable solids are considered non-settleable is that their small size means that their surface area is large compared with their weight. This means that their settling velocity is low enough that they will not settle out in any reasonable amount of time.

An additional factor, which normally acts on colloidal particles, is the effects of charge. Each particle tends to have a negative surface charge, which will repel others and prevent them from forming a larger particle with a higher settling velocity. This surface charge is referred to as zeta-potential. It acts to oppose the van de Waals force which causes all particles to attract each other. As long as the zeta-potential force is stronger than the van de Waals force then the particles do not settle out at all. Table 2.1 shows the size ranges of typical turbidity particles present in water.



#### Table 2.1 Size ranges of some turbidity particles. Source [AWWA 1995]

Dissolved materials, such as salts, chemicals or gases also cannot be removed by settling. Most of the trace metals and organic chemicals found in water are dissolved. These are often the cause of taste, odour and colour complaints from customers, in addition to the health problems associated with many metals. These dissolved materials need to be removed by precipitation, as they are impossible to filter out.

Visible turbidity in drinking water is objectionable to customers and, more significantly, can shield the harmful micro-organisms from contact with the disinfectant.

## 2.3.2 Measurement of Turbidity

A light beam is passed through the sample water and the particles absorb and scatter the light. Turbidity instruments are based around photoelectric detectors, which are sensitive to very small changes in light intensity. In high turbidity samples this can be used to measure the attenuation of transmitted light through a fixed-volume sample.

However these are limited in their ability to measure high or extremely low turbidity. At low scattering intensities, the change in transmitted light, viewed from a coincident view, is so small that it is virtually undetectable by any means. Typically, the signal is lost in the electronic noise. At higher concentrations, multiple scattering interferes with direct scattering.

The solution to this problem is to measure the light scattered at an angle to the incident light beam and then relate this angle-scattered light to the sample's actual turbidity. A detection angle of 90° is considered to be very sensitive to particle scatter. Most modern instruments measure 90° scatter as shown in figure 2, [Sadar 1998].

These instruments are called nephelometric turbidity meters, to distinguish them from generic turbidity meters, which measure the ratio of transmitted to absorbed light. The intensity of scattered light is measured in Nephelometric Turbidity Units (NTU) which are calibrated to a primary standard of Formazin to ensure consistency between meters.



#### Figure 2.2 Measurement of turbidity by nephelometry. Source: [Sadar 1998]

The angle of peak scatter and the amount of light scattered are both influenced by the size distribution and nature of the particles. Because of this, there is no direct relationship between the amount of suspended matter and the turbidity measurement.

Nevertheless, nephelometric turbidity measurement is very reliable and is the standard way of measuring turbidly in drinking water. The nephelometric turbidity meter calibrated to a standard Formazin solution is the only instrument approved by standards bodies, such as the US Environmental Protection Agency and the NZ Ministry of Health.

#### 2.3.3 Cryptosporidium

One particularly troublesome protozoa is Cryptosporidium. It has been found in cattle, sheep, swine, goats, dogs and cats as well as a wide variety of wild animals including deer, rabbits, possums and squirrels. Surface water sources around the world are widely contaminated with this protozoa.

Cryptosporidiosis (the illness caused by infection with Cryptosporidium) is characterised by gastroenteritis and diarrhoea. It can be potentially fatal to the elderly and people with weakened immune systems. Cryptosporidium is known to be widely distributed in natural water systems in New Zealand [Ionas et al. 1998]. A survey done by Duncanson et al (2000) indicates New Zealand has a high rate of cryptosporidiosis compared to other developed countries. This probably relates to the number of people using small scale private water supplies. Indeed, even rural roof-collected rainwater supplies have a significant bacteriological content with cryptosporidium present in 4% of cases in a recent survey of the Auckland region [Simmons et al. 2001]. However a very low rate of cryptosporidiosis was observed in people using water treated in accordance with the applicable standards.

Cryptosporidium is quite resistant to disinfection, particularly if there is other turbidity present in the water to shield it from the disinfectant. It is critical that the physical removal processes do a through job. While filtration is the main barrier to the passage of protozoa cysts, the coagulant dosage is the most important factor for optimal removal [Logsdon et al. 1993].

The events of May 2000 in small town of Walkerton, Ontario, Canada is often referred to as evidence of the significance of microbiological contamination of drinking water. Seven people died from drinking water contaminated with a deadly strain of E. coli bacteria. Proper chlorination of water would have prevented the tragedy, as bacteria are significantly more vulnerable to disinfection than protozoa, but also more dangerous. In this town of 5000, 2,300 people were sickened. It was found that water from the underground water source became contaminated with manure spread on a farm near the town. The operators most directly responsible are facing criminal charges, but this is considered to be a failure of the whole system.

# 2.4 Coagulation and Mixing

## 2.4.1 Coagulation

Coagulation can be defined as the process of destabilising the non-settling particles such that they are no longer stably suspended and can be removed.

The behaviour of the particles in water is strongly influenced by their electrostatic charge. This charge comes about because of the uneven surface characteristics of the particles and in most solids is negative, particularly the alumino-silicate clays typically suspended in surface water. This means that the negative charges on each particle will repel others and prevent effective agglomeration and flocculation. This charge is measured by using zeta-potential or streaming current. The zeta-potential and streaming current measurements are covered in more detail in chapter 4.

Therefore the main mechanism in which coagulation works is charge neutralisation. The positively charged coagulant ions absorb onto the surface of the particles, neutralising the negative charge. When the charge is near neutral the colloidal particles will not be repelled by each other and so natural collisions will eventually cause them to agglomerate together because of the van de Waals force. The larger resulting particles will settle much more rapidly.

## 2.4.2 Mixing

The coagulant must be distributed quickly and evenly throughout the water. Some form of mixing is always required for this. The most widely used method is some variety of

mechanical mixing, generally some sort of propeller or paddle arrangement. These are also called backflow mixers as water in the chamber is always blended with incoming flow, a typical one is shown in figure 2.3. The chambers typically provide detention times of 10-60 seconds.



Figure 2.3 Propeller type mechanical mixer. Source [AWWA 1998]

By comparison, the more modern inline mixing methods might operate at detentions time around 1 second and much higher mixing intensities. A number of designs exist for this, two of which are shown in figure 2.4, all methods involve high energy injection of the coagulant directly into a water line. Recent experience shows this is more effective in many situations.



Figure 2.4 Two types of inline mixers. Inline blender (Left), pump mixer (Right) Source [AWWA 1998]

Other, less common, approaches to mixing include 'hydraulic mixing' using specially designed weirs and chambers or 'air mixing' by blowing compressed air into the water.

A wide variety of materials can function as coagulants, however trivalent metal ions have the highest charge density and are by far the most effective.

#### 2.4.3 Aluminium Sulphate (Alum)

Of the trivalent ions, Aluminium is the most commonly used in water treatment in the form of Aluminium Sulphate,  $Al_2(SO_4)_3.14H_2O$ . In industry it is referred to as 'alum' for convenience.

Alum works in two ways: charge neutralisation and sweep floc.

Sweep floc is the effect where Aluminium hydroxide precipitates form and greatly increase the effectiveness of coagulation both by increasing the rate of collisions and enmeshing the colloids.

How much effect each mechanism has will depend on both the alum dose and the pH. Sweep floc is significant above alum doses of around 30ppm and at higher pH levels, under other conditions both mechanisms participate depending on pH. The reaction that occurs is:

$Al_2(SO_4)_3 + 3Ca(HCO_3)_2 + 6H_2O$	$\rightarrow$ 3CaSO <sub>4</sub> +	$2Al(OH)_{3} +$	$6H_2CO_3$
Alum + Alkalinity	$\rightarrow$	Aluminium + Hydroxide	Carbolic Acid

Excess alkalinity is required for this reaction to work properly; otherwise the carbolic acid will cause the pH will be lowered to a point where soluble aluminium ions  $(Al^{3+})$  are formed instead of aluminium hydroxide. Dissolved aluminium is not an effective coagulant and will cause problems when it comes out of solution later in the treatment process or reticulation system.

Figure 2.5 shows the effect of various alum dosages on typical high turbidity water. Here the optimum dose is at around 47 ppm, which corresponds to a slightly negative residual particle charge (zeta-potential), the best dosage is probably slightly offset from zero zeta-potential because of the sweep-floc coagulation action.



Figure 2.5 Typical final turbidity and zeta-potential as a function of alum dose. [Source Zetameter 1993]

The pH after alum dosing has a significant effect; the graph in figure xx would be shifted significantly by changes in both raw water pH and alkalinity. This is because there is a complex relationship between pH and the amount and types of Aluminium Hydroxide formed. Different types of Aluminium Hydroxide have different structures and effects on coagulation.

Alum dosages required are typically in the region of 16 ppm for protected reservoir sources, 22 ppm for normal lakes, and 30 ppm for rivers under normal conditions. It can be significantly higher, such as 40-50 ppm under high turbidity conditions such as floods.

#### 2.4.4 Other Coagulant Chemicals

Poly-aluminium chloride  $Al(OH)_x(Cl)_y$  is efficient in waters which require less pH adjustment and produce less sludge. This is not normally used with a flocculant aid.

Other coagulant chemicals that are sometimes used include Irons salts, such as Ferric Chloride  $FeCl_3$  and Ferric Sulphate  $Fe_2(SO_4)_3$ . These work over a wider range of pH values than alum and can sometimes be more effective in removing organic matter.

Various long chain cationic polymers can be used as coagulants or as a flocculant aid in conjunction with other primary coagulants.

In this thesis the terms 'coagulant' and 'alum' can be used interchangeably as all the work was done with alum, however 'alum' is used in referring to a specific set-up or experiment which used alum and 'coagulant' in referring to general situations where any of the range of other coagulants could potentially be used.

# 2.5 Flocculation and Clarification

The next treatment stage is flocculation, which is the build-up of larger particles from the smaller particles newly destabilised by coagulation.

In practice, flocculation happens immediately whenever there is coagulation. However the two processes are normally considered separately. Coagulation is considered to be a chemical effect and to happen almost immediately on mixing, while good flocculation takes considerably longer and depends on the physical mixing of the water.

The destabilised colloids may combine together into small micro-flocs during the rapid mixing part of coagulation, but do not combine into larger macro-flocs until the gentle mixing process of flocculation allows enough collisions between particles to occur without breaking up the flocs. The goal of flocculation is to maximise the amount of collisions between particles, which allows for the largest agglomerated macro-flocs to form.

The flocculator, where most flocculation occurs, is commonly a basin, or series of basins, with baffles to create a consistent gentle mixing as water flows through it. Gentle mechanical mixing will enhance this, although the simple series of baffles is normally sufficient. Figure 1.xx shows an example of the most common type of flocculator.



Figure 2.6. Typical Propeller Mixer and Baffled Flocculator . Source [Bratby 1986]

Additional chemicals are sometimes added before or during flocculation to improve the size and strength of the flocs formed. These additives are called flocculant aids or coagulant aids. They have the advantage of increasing the rate of settling in the clarifier and reducing the volume of sludge that needs to be disposed of. It can also sometimes reduce the amount of primary coagulant needed.

The most common flocculant aid chemicals are polyelectrolytes. These are long-chain polymers, which dissolve in water. The polymers used can form either positive (cationic) or negative (anionic) ions in water. Cationic polymers can be used as primary coagulants, but it is normally more efficient to use them as a flocculant aid with a metal salt coagulant. Polyelectrolytes are very effective flocculant aids, and are typically used at concentrations of only around 1ppm. Figure xx illustrates the difference between micro-flocs and macro-flocs and the effect of the polymers.



Figure 2.7 Floc formation with polymers. Coagulation (top) and flocculation (bottom)

Clarification is the following process where the settling floc is actually separated from the water. This is also called sedimentation or settling. One of the most common types of clarifier is the centre fed up-flow clarifier.

The position of the sludge is clearly visible within the clarifier, the boundary between the sludge and clarified water appears surprisingly solid and consistent. The height of the sludge blanket in a clarifier can vary considerably and depends strongly on the settling velocity of the flocs as well as the amount of material trapped in the clarifier.

Although coagulant dosage can be determined by instrumentation or jar tests, flocculant aid dosage is normally determined by visual inspection of the sludge blanket in the clarifiers. There is often a direct correspondence between polymer dosage and the position of the top of sludge blanket. Operators typically adjust the flocculant aid dosage to keep the sludge blanket 'height' at a level that experience shows results in the best operation.

As the amount of floc sludge trapped in the clarifier increases the thickness of the sludge blanket increases. If the sludge is not removed before it gets too thick then solids can become re-suspended and be carried through. The removal procedure involves emptying the sludge from the bottom of the clarifier. Some manual hosing or mechanical scraping of the clarifier walls may also be required. Smaller plants can simply dump their sludge directly, while in large plants it must be further treated to thicken it for disposal in a landfill. While final water quality is always the most important factor in treatment, the ease of sludge disposal is often an important aspect of coagulant and flocculant aid selection and dosage.

There are a wide range of clarifier designs and coagulant and flocculant chemistries that are used around the world. There are also water treatment methods that do not involve clarification at all. However, up-flow clarifier with alum and polymer is the design used almost exclusively in large plants in New Zealand and is the most common type of large plant worldwide.

## 2.6 Jar Tests

Jar tests are the only way to determine the effectiveness of the coagulation/flocculation process. A jar test is performed by simulating the chemical dosing and mixing that would occur in the real plant in a jar. The floc in the jar is then allowed to settle, and the resulting turbidity indicates the level of effectiveness of the coagulation/flocculation regime being tested.

Jar tests are carried out extensively during plant design or upgrades and during major changes in plant operation. The jar test are the best way to evaluate the effect of all factors that could affect coagulation/flocculation. These include:

- 1. The type of coagulant used
- 2. The coagulant dosage
- 3. pH of the dosed water. This may require the raw water to be pH corrected.
- 4. Type and dosage of flocculant aids
- 5. The sequence of chemical additions and the time in between them
- 6. The intensity and duration of the rapid mixing

7. The velocity gradients applied during gentle mixing.

The normal procedure to establish the optimum conditions for the overall process is to sequentially optimise each parameter while holding the rest constant [Bratby 1980 pp 263-289]. Repeated iterations of this procedure will generally locate the optimum conditions for settling in the jar. Unfortunately, the effectiveness of flocculation and settling are extremely dependant on the physical mixing and circulation, which does not scale well. It is well recognised that jar tests are only indicative of results that would be obtained from the real plant. The difference can be minimised by matching the mixing intensities in the jar with the real plant. Mixing intensity is defined as the root-mean-square of velocity gradient (rate of change of velocity) which is expressed in units of m/s/m or s<sup>-1</sup>. This is a function of power input, dynamic viscosity and volume.

The apparatus for performing jar tests is a set of identical jars, normally 5. All the jars have stirrers, which are connected together to an adjustable speed drive. A modern jar tester allows a selectable series of stirring speeds to be applied automatically in sequence. Figure 2.8 shows a typical jar testing apparatus.



#### Figure 2.8 Simplified Diagram of a Typical Jar testing Apparatus

During normal plant operation all of the above process parameters are fixed, apart from the coagulant and flocculant aid dosages. These must be adjusted to compensate for variation in raw water character and quality.

The following is a typical correct procedure for establishing the coagulant dosage by jar tests:

- 1. Take 5 samples of raw water. Use a pipette to add diluted coagulant solution such that each jar has a different concentration of coagulant bracketing the expected optimal dosage. For example if the best alum dose is known to be around 27 ppm then dosages of 20,24,28,32,34 ppm might be used.
- 2. Run the stirrer for 5 minutes at 300rpm to simulate the rapid mixing for coagulation to occur.
- 3. Run the stirrer for 20 minutes at 30 rpm to simulate gentle mixing for flocculation to occur.
- 4. Turn off the stirrer and allow 30 minutes for the floc to settle.

- 5. Take a sample from below the surface of each sample and record its turbidity.
- 6. Select the best dosage. Or preferably, plot the results and estimate a curve of best fit, then select the dosage that corresponds to the minimum.

A visual observation of the floc and settled turbidity is seldom sufficient to accurately distinguish between the best jar result and the ones next to it. Obtaining an accurate, repeatable and quantitative result does require use of a turbidity meter. It is important that the sample from below the surface of the jar be drawn off without disturbing the settled floc or the surface scum and this sample introduced into the measuring chamber of a laboratory turbidity meter.

However, it has been the author's experience that only the largest plants in New Zealand have a laboratory turbidity meter available to use in their jar tests. The result of this is that jar tests are often performed in only 5ppm increments of coagulant and the best one chosen. It is likely that this procedure will produce results that are only accurate to within a 10ppm range, even when performed by experience operators.

The optimal flocculant aid dosage is more difficult to obtain from jar tests because there is often no minimum result (above which things get worse). Also inconsistencies in timing and handling can have a more significant effect.

# 2.7 Online Control of Coagulant Dosage

Determining the optimal dosage of coagulant by jar tests is a relatively time consuming manual process, and is therefore less than ideal in situations where the raw water quality tends to vary.

The charge on the particles (Zeta-potential) has been found to be the most useful single measurement to make in predicting the effectiveness of varying coagulant dosages. Therefore an instrument that approximates the zeta-potential measurement, the streaming current meter, is commonly to measure this in water after coagulation. This is covered in detail in chapter 3.

The coagulant dose is adjusted to maintain the same streaming current reading, even as the source water changes. This results in reasonably consistent effectiveness over a range of raw water characteristics. The controller that performs this function is an important part of the treatment process. Traditional and advanced controllers for coagulant dosage are discussed in detail in chapter 4.

As effects other than charge are significant, jar tests need to be done to establish the SC that corresponds to the best coagulation. Ideally this should to be repeated relatively frequently, whenever the raw water parameters other than particle charge may have varied enough to affect the coagulation mechanisms.

# 2.8 Modelling for the Automation of Coagulant Dosing

All the previous automated systems that have designed to attempt this problem are based on numerical models. These models relate alum dose and a number of other parameters with the clarified water turbidity; this information can be used to determine the best alum dose for the conditions. The most successful models have been based on a neural network (NN), also called an artificial neural network (ANN). NNs are a very flexible method of fitting a model to relationships between input and output data and are widely used in situations where there is an incomplete (or non-existent) theoretical understanding of the process to be modelled.

Gagnon et al. (1997) developed a model for predicting the optimal alum dose from measured turbidity, pH, temperature and conductivity for the Ste-Foy water treatment plant in Quebec, Canada, using up to 6 years of data.

Evans et al. (1998) developed a neural-fuzzy model for predicting the operator selected alum dose from turbidity, colour, pH, temperature, conductivity and flow for the Huntington Plant in England, using 150 days of data.

Baxter et al. (1999) developed a NN model of natural organic matter removal as a function of 12 water and process parameters using three years of data from the Rossdale water treatment plant in Edmonton, Canada. This model also involves a time-delayed input of turbidity and colour, making it a dynamic model. Zhang and Stanley (1999) used this as the basis for a proposed inverse control system for coagulant dose.

van Leeuwen et al. (1999) developed a model of optimal alum doses based on jar tests conducted on surface waters collected in a range of southern Australian locations. The parameters used were turbidity, colour, UV absorbance (at 254nm), alkalinity, pH and dissolved organic carbon. Maier et al. (2004) extended this modelling to involve both forward and inverse models to allow manipulation of different parameters.

Joo et al. (2000) modelled alum dose from turbidity, temperature, pH and alkalinity for the Chungju water treatment plant in Korea, using 2 years of data.

Yu et al. (2000) modelled alum dose at a water treatment plant in Taipei City, Taiwan, as a function of raw and clarified water turbidity, pH and conductivity, using 1 year of data at 15 minute intervals.

Bai et al. (2002) used two years of jar tests to model required alum dose as a function of turbidity, colour, pH, temperature and river flow for the SongHua River in Harbin, China.

A number of these studies also concluded that NN modelling compared very favourably with linear modelling. A generally good level of accuracy has been obtained by these models, although the range of different performance criteria used makes direct comparison difficult. The predictions seem to be generally in the 5-15% range of accuracy.

The streaming current measurement, either as a modelled parameter, or for online control, does not factor in any of the models.

To the best of the author's knowledge, there has been no success using even the most advanced of these systems as more than advisory tools for the human plant operators.

This sort of system will generally be specific to a particular plant or region and require specialized design. This use of a model for control of the coagulant dosage can be considered a feed-forward control design, because the output from the clarifier is not

directly used in determining the input dosages. It is not practical to use clarifier output to control chemical dose because it is always too slow to respond to input changes.

However, there are benefits to modelling the process in this way. The model can indicate to plant operators when raw water parameters have changed enough to require jar testing and they potentially allow an appropriate response to large changes that occur faster than they can be tracked with jar tests. In addition, they can be used as virtual laboratory interfaces in order to gain a better understanding of the factors that affect unit processes, to conduct historical scenario analysis and to train new operators (Baxter et al., 2001).

Indeed an online model-based system could potentially be implemented to control coagulant dosage based on measurements of raw water parameters. The coagulant dose would then be optimal to within the 5-10% accuracy of the models, which is often actually better than obtained by manual control, even with the use of jar tests. Unfortunately this is only true if the conditions match those under which the NN training data was gathered. Parameters such as alkalinity and dissolved organics can only be measured offline and so models, which depend on them, cannot be used for online control. It is likely that the models that do not depend on these factors require them to be constant.

The composition of the raw water is clearly a very important factor in the chemical dosages required. For example Franceschi et al (2002) conducted jar testing study examining treatment of solutions of two different types of clay (Bentonite and Kaolinite) with alum. This indicated, among other things, that the relative amounts of Bentonite and Kaolinite in the water have a significant effect on the alum dosage required. This is significant as measurement of turbidity and other online raw water measurements cannot distinguish between these two types of clay.

This would cause significant problems if a flood condition or the mixing or multiple raw water sources for treatment resulted in a change in raw water composition unknown to the model.

Although a number of these studies refer to the determination of the 'optimal' coagulant dose, what is being performed is not strictly optimisation; it may be more properly described as modelling and inverse control.

In this work it is the use of the automated jar tester that enables the use of an optimiser. This attempts to optimise coagulant dose (or streaming current set point) to minimise post-clarifier turbidity by using jar test results as an indication of future turbidity. This is fundamentally different from any work that has been published previously. Indeed searches of academic and technical literature, even internet searches using the most popular search engines, yield no evidence of coagulant dosing control using systems other pre-designed models, streaming current meters or manual jar tests.