EPA DRINKING WATER ADVICE NOTE
Advice Note No. 15:
Optimisation of Chemical Coagulant Dosing at Water Treatment Works

Office of
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1. INTRODUCTION

Successive EPA reports on The Provision and Quality of Drinking Water in Ireland have shown that although compliance with the aluminium indicator parameter in Ireland has improved since the *European Communities (Drinking Water) Regulations (No. 2), 2007* **came into force in March 2007 it remains problematic in some supplies. Although compliance has improved it still remains unacceptably low (98.7% in 2012). These non-compliances mainly arise from the use of aluminium based coagulants as part of the treatment processes at water treatment plants in surface water sources where there is inadequate management and control over the chemical coagulant dosing processes.**

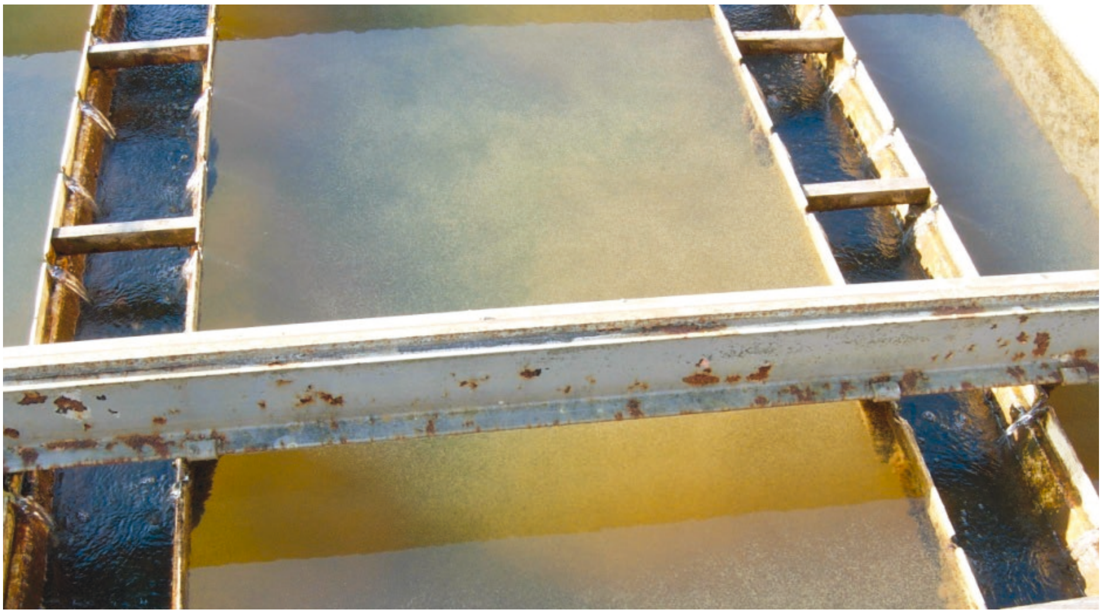

FIGURE 1. Example of Coagulant Carryover

While these non-compliances are not a cause for health concern in themselves, aluminium is an important indicator of the efficiency of the operation of the treatment plant. The presence of elevated levels of aluminium in treated drinking water indicates that the plant is not operating adequately and other more significant parameters may be coming through the treatment plant and into the final water. EPA audits and investigations into aluminium non-compliances indicate that poor control over the coagulation process at treatment works is the likely cause.

In 2012, the Office of Environmental Enforcement (OEE) commissioned WRc to undertake a review to identify technologies available and suitable for use in Ireland that can improve and optimise the control of coagulant chemical dosing at water treatment plants. This review was conducted under the supervision and guidance of the EPA and South Tipperary County Council. The report prepared as part of this review has been used as the basis for this advice note.

This Advice Note has been prepared to provide technical guidance on the selection and implementation of coagulant dose control technologies. It gives guidance on the options that are applicable in Ireland and provides brief guidance on the information that must be collated by a water supplier to inform the selection of the appropriate technology and assist optimisation of coagulant dose. This Advice Note is intended to provide additional advice and guidance to that provided in the EPA *Water Treatment Manual: Coagulation, Flocculation and Clarification* and should be read in conjunction with this manual.

2. COAGULATION PRACTICE

2.1 GENERAL

Several factors affect the effectiveness and efficiency of chemical coagulant dosing at water treatment works. A review of plant operations should take place prior to any remedial works to ensure that any resource expended optimising plant operation is focused on where it is likely to be most effective. This review should examine various aspects of the treatment process that influence the effectiveness of coagulation such as raw water chemistry (alkalinity), selection of coagulants, chemical dosing and dispersion, order of dosing, pH Control and flocculant aids. This advice note should be considered in tandem with EPA Drinking Water Advice Note No,4: Disinfection By Products in Drinking Water.

Automation of chemical dosing can aid and improve compliance but if the process design is flawed, then effectiveness will be compromised. Installation of automatic coagulant dose control will only correct deficiencies relating to incorrect dose selection; it cannot overcome deficiencies in the design of a coagulation process.

2.2 SELECTION OF CHEMICAL COAGULANTS

The commonly used inorganic coagulants are aluminium sulphate (“alum”), polyaluminium chloride, ferric sulphate and ferric chloride. Selection is a function of cost, raw water quality and (sometimes) the treatment process.

For soft, coloured, waters, either aluminium or iron coagulants may be used at their respective optimal pH ranges: 6.5 to 7.5 for lowland surface waters or 5.5 to 6.5 for highly coloured upland waters (aluminium) and 4.0 to 5.0 (iron). Iron coagulants can have an advantage relative to aluminium in this application, as operation at a much lower coagulation pH can be used to maximise the removal of dissolved organic matter and consequent reduction in the potential for THM formation.

For harder waters, iron coagulants are often used if coagulation pH values of 8.0 or more occur – such pH values would not be appropriate for aluminium coagulants unless separate acid dosing were applied. Increasing the dose of metallic salt will further depress the pH but will result in a very undesirable increase in the soluble metallic content of the water, which will carry through the filters to supply. Dosing with a strong mineral acid, such as sulphuric acid, will depress the pH without the unwelcome increase in the soluble metallic content of the water.

In some situations it has been found that a change of coagulant can lead to improved performance of a clarification process, particularly with higher rate processes such as Dissolved Air Flotation (DAF).

Further guidance on the chemicals used in coagulation/flocculation is given in Chapter 2 of the EPA *Water Treatment Manual: Coagulation, Flocculation and Clarification*. Chapter 3 and Appendix B provide guidance on determination of the appropriate chemical coagulant dose. This guidance is not repeated in this Advice Note and water suppliers should refer to the relevant sections of the EPA *Water Treatment Manual: Coagulation, Flocculation and Clarification.*

2.3 COAGULANT CHEMICAL DOSING AND DISPERSION

2.3.1 DISPERSION OF COAGULANT

A key requirement is to achieve rapid dispersion of coagulant, as this can impact on process performance in terms of entrapment of particulate matter and ensuring even distribution of dose between process units downstream of the dosing point. Because poor dispersion means that a proportion of the water is under-dosed, the operational response is typically to increase the dose to compensate, which impacts operating costs as well as potentially contributing to higher residual coagulant metal concentrations in treated water. Poor dispersion might also adversely affect the stability of a feedback dose control system which relies upon a representative sample of coagulated water, particularly if the sample is drawn from close to the dosing point.

The factors to consider are the current provision for dispersion (mechanical or static mixers; hydraulic mixing by turbulent flow or weirs), how the chemical is initially dosed (spreader bar, single or multiple point injection) and the state of the chemical at the point of dosing (is carrier or dilution water required, and if so how much). As for the actual time required, where coagulation is used in conjunction with floc blanket clarifiers or dissolved air flotation it is unlikely that extremely rapid (< 1s) dispersion is necessary; achieving dispersion in a few seconds should be sufficient.

A standard method for assessing the effectiveness of dispersion is described in Appendix A.

Once coagulant has been dispersed, floc will start to form and excessive turbulence should be avoided once visible floc has formed. In this respect, weirs should not have a greater fall than 0.5 m, and water velocities should be less than 0.3 m/s, in order to ensure that floc are not broken.

FIGURE 2. Coagulant Spreader Bar

2.3.2 DISPERSION OF ACID OR ALKALI

Where acid or alkali is used, this needs to be dispersed quickly so as to ensure that the time between the dose point and a stable pH being measurable in the process is acceptably short. As with coagulant, the use of dilution water and dosing at a point of turbulence supports rapid dispersion.

The use of dilution (or carrier) water with strong alkalis (sodium hydroxide and lime) will result in scaling problems if the total alkalinity of the water is greater than about 40 mg $CaCO_3$/l. In this case options to prevent scaling include either de-carbonating the dilution water or simply dosing the undiluted alkali. More detail on lime dosing is given in Section 2.5.2.

2.4 ORDER OF DOSING

The order in which coagulant and pH adjustment chemicals are added may impact on floc quality. It may be optimal to add acid or alkali upstream of the coagulant so that the desired coagulation pH is achieved rapidly just after the point of coagulant addition. In the case of low alkalinity waters, typical practice is to dose alkali before coagulant. This is to avoid the loss of carbonate alkalinity (to dissolved carbon dioxide) that might result from addition of the acidic coagulant. Against this, there is evidence that for some waters and coagulants it is beneficial to make the pH adjustment after coagulant addition. The optimal order in which coagulant dosing and pH adjustment should be investigated at each plant.

Jar testing can be a useful guide to whether order of addition is a significant factor for a given site (see Appendix C of the EPA *Water Treatment Manual: Coagulation, Flocculation and Clarification.*

2.5 CONTROL OF COAGULATION PH

2.5.1 PH MEASUREMENT AND CONTROL

Coagulation pH is the stable pH value that is achieved after coagulant and alkali or acid have been dosed to raw water. Measurement of coagulation pH is one of the most demanding water quality measurements because of the fouling potential of the water and inherent difficulties with pH measurement, particularly in waters of very low ionic strength (“thin” waters).

The current best guidance on measuring the pH of waters with very low ionic strength, based upon a thorough evaluation at an upland site, is as follows:

- Use a flowing reference electrode. Such electrodes keep themselves clean and avoid possible reaction between a reference gel and the sample. Standard pH buffers work as well as low ionic strength buffers and the probes can be returned to service just as quickly.
- Provided there is a flowing reference, standard buffers at pH 4 and 9 should be used followed by a validation reading at pH 7. The use of pH 10 buffers is not recommended. pH buffers should be kept at the same temperature as the sample by immersing in a holder in the flow cell system. The buffer must be valid over the full sample temperature range.
- The flow cell needs a clean electrical earth contacting the liquid to reduce electrical noise.

More general guidance on pH measurement for coagulation control on all waters is:

- Sample should be taken from the centre of a pipe not from the bottom.
- Consider using a dual large basket strainer in the sample line (to enable one basket to be cleaned while the other is in service), this will help keep the pH probes clean.
- A small open Perspex tank with the probes dipping into it is better than a closed flow cell as: it avoids pressure problems; the probes are visible and can be removed individually for maintenance. A baffle should be fitted across the tank to force the flow upwards against the pH electrode surface - this helps with cleaning and response time.
- There should be a low flow alarm.
- Citric acid is often effective when used for automatic cleaning of pH sensors.
- Dual or triple pH sensors should be considered with a predefined difference between the two sensors used to trigger an alarm.

- The calibration procedure or checking must include a check of the response time of the system when it is returned to the sample. Most pH probes can reach a condition where they calibrate correctly but respond very slowly causing control loop problems.

2.5.2 LIME DOSING SYSTEMS

Lime is the most widely used alkali for coagulation pH control. It is most commonly delivered to site in its hydrated powdered form, stored in silos, and then dosed as a slurry. Lime dosing systems can be problematic, but reliable operation is achievable if good design practices are followed.

Stable pH control will be difficult to achieve if the lime dosing system does not produce a consistent slurry concentration or if inadequate contact time is allowed for dissolution after dosing. How these potential shortcomings can be avoided by proper specification of the key elements of a lime-dosing system is outlined below.

PRODUCT QUALITY

Lime used in potable water treatment must comply with the prevailing European standard (currently EN 12518 – 2008). Free moisture content should ideally be less than 0.5%, to keep the powder free-flowing in storage.

STORAGE

Ideally there should be more than one silo, each sized in excess of a full delivery to allow for some remaining product. Load cells are the preferred means of monitoring contents. Silos must have air filters to prevent escape of lime dust during filling; a high-level indicator (independent of the contents monitor) to help prevent over-filling; pressure relief to prevent over-pressure during filling; vacuum relief to prevent under-pressure during abnormally rapid discharge; and some form of discharge aid.

If space only allows one silo it should have two outlets. Each silo outlet should have independent lime transfer to the slurry make-up tanks. Transfer is generally by screw conveyor, but may be by air conveying for longer distances, or is sometimes direct feed.

SLURRY MAKE-UP

Batch make-up is recommended over continuous, to avoid scaling problems and to achieve greater consistency in concentration. Current practice is towards relatively dilute slurries (in the region 2% w/w), to provide pipe velocities high enough to prevent settlement and to obviate the need for carrier water. Three batch tanks are preferred to two, since the additional tank enables greater consistency in concentration, and assurance of adequate stabilisation time (15 to 20 minutes is suggested to allow for any softening reactions to complete within the tank, to minimise scaling of downstream pipework), in the event of one tank being out of service. Slave weigh hoppers offer greater consistency and accuracy than volumetric feeding or load cells, especially when producing relatively dilute slurries where the quantity of lime is small relative to the quantity of water.

DOSING

Because lime is dosed as slurry, the dosing arrangement must provide both good initial dispersion and adequate contact time for dissolution. Dissolution of hydrated lime slurries can take up to three minutes, depending on lime quality. The pH control measurement should not be taken until dissolution is complete, to avoid unrepresentative sampling (Watts, 1990).

Softening reactions will occur at the point of dosing unless the receiving water is of low alkalinity (< 40 mg/l $CaCO_3$). If dosing into an open channel, scale formation on the dosing pipe can be minimised by leaving an air gap between pipe and water surface, with the slurry discharge just prior to a weir or other point of high turbulence. If dosing into a pipe, duplication of dosing points is essential, with a regular cycle of switchover and descaling. Single-point dosing is recommended unless pipe diameter is greater than about 1.4 m.

2.5.3 ALTERNATIVES TO HYDRATED LIME

QUICKLIME

Quicklime is cheaper than hydrated lime and has a higher specific neutralising capacity, so smaller silos can be specified. It does require slaking (the addition of water), for which a proprietary batch system is available; the efficient operation of this system requires a minimum throughput, and it appears to be best suited to works with a large lime usage (> 500 tonnes/y). The particle size of the resultant slurry is smaller than hydrated lime slurry, so dissolution is more rapid. Some grades of quicklime contain relatively high proportions of calcium carbonate, which may give rise to turbidity problems if dosed after the last filtration stage. This means that care must be taken when interpreting turbidity results after addition of quicklime as it is not necessarily an indicator of poor filter performance.

STABLE LIME SUSPENSION

Suspensions of lime with very small particle size are commercially available. They are expensive relative to lime powder (higher operating cost), but easier to handle (lower capital cost). Storage tanks must be provided with some agitation to prevent settlement, either by stirring (flat-bottomed tanks) or recirculation (silo type tanks with conical outlets). Pipework that is outdoors or passes through unheated buildings should be trace heated and lagged. The balance of higher operational/lower capital costs makes lime suspension cost-effective, relative to powdered lime, for installations with a lime consumption of up to about 60 tonnes/y. The smaller particle size means that dissolution is appreciably more rapid than conventional lime slurry.

SODIUM HYDROXIDE

Sodium hydroxide (caustic soda), typically delivered as 47% w/w solution, is likely to be similar in cost to stable lime suspension (market price can be volatile), but being more concentrated requires less volumetric storage capacity. Protection against low temperature is essential because of its high freezing point. Because it is a liquid, no dissolution time has to be allowed for after dosing beyond that needed for it to become uniformly dispersed in the process. It is an economically viable option for smaller works with an equivalent lime consumption of up to about 60 tonnes/y.

LIME WATER

Provided high quality lime (to minimise insoluble material) is used, batch make-up of saturated lime solution (lime water) is a relatively simple and reliable process. However, the lime concentration is very low (e.g. 0.165% w/v at 20 °C) so batch tanks and dosing pumps must be an order of magnitude greater in size than those used for slurry systems of equivalent capacity, which substantially increases the capital costs and footprint.

SODIUM CARBONATE

Sodium carbonate (soda ash) is straightforward to handle as it has good solubility and has the potential advantage of increasing pH buffering capacity. It can be markedly more expensive than lime, and this usually restricts its use to smaller works. It is dosed as an aqueous solution and, unlike lime, only a few seconds should be needed after it has been uniformly dispersed in the process to allow pH value to stabilise.

2.5.4 ACID DOSING SYSTEMS

Where the source water is very alkaline, coagulant dosing may not reduce the pH to optimum levels for coagulation. The optimum pH has been achieved in some such plants by increasing the alum or ferric dose until the optimum pH has been achieved. This practice should be discontinued as an unnecessarily large dose of coagulants is required to achieve this with the associated risk of carryover into the final water. The most commonly used acid to reduce coagulation pH is sulphuric acid (H_2SO_4).

Sulphuric Acid (H_2SO_4) is a colourless oily liquid, available in various concentrations. It is a highly corrosive strong mineral acid. It is used occasionally in water treatment to depress the pH of water. If required to be diluted, sulphuric acid must be added very slowly to water. A chemical feed pump made from corrosion resistant material is used. Manufacturer's recommendations should be examined before purchasing an acid injection system. Sulphuric acid must be stored in accordance with Material Safety Data Sheet instructions provided and safety precautions should be strictly observed when handling it.

Jar tests should be used to determine the optimum coagulant pH using coagulant alone. The dose of coagulant in the jar tests should then be reduced in tandem with a corresponding increase in the acid dose such that the pH remains constant, Varying the coagulant dose and acid dose while keeping the coagulant pH constant will indicate the actual amount of coagulant required to optimise coagulation. If the pH at the required dose of coagulant is not optimal the pH should be depressed using acid. For the reasons outlined above it is not advisable to depress the pH using coagulants.

2.6 FLOCCULANT AID DOSING AND DISPERSION

Polyelectrolyte flocculant aids are used to enhance floc settlement. The polymers bridge the microfloc formed by coagulation, agglomerating smaller particles into larger ones. As with coagulant, if dispersion is poor it is likely to result in overdosing. In addition to the cost implications, overdosing may result in the accumulation of gelatinous sludge in clarifiers and, in the longer term, irreversible binding of filter media. The symptom of such media binding is an upward trend with time in the headloss measured across the filter bed after it has been cleaned by backwashing.

Microfloc arising from coagulation are already forming upstream of the flocculant aid addition, so the mixing of the flocculant aid should be of relatively low intensity. Other than the risk of fragmenting the microfloc, excessive shear is deleterious to the polymeric bridging which is the intended action of the flocculant aid.

Concentrated polyelectrolyte solutions are highly viscous and must be diluted in accordance with the supplier's instructions; both the lower viscosity and the higher volume arising from dilution assist dispersion. Dilution may also help achieve specific hydraulic conditions necessary for a particular dosing arrangement, an example being a spreader bar in which a minimum velocity will be required to ensure an even flow distribution to each orifice. If using cationic polyelectrolyte there may be some risk of slight hydrolysis if chlorinated water is used for dilution, resulting in the blockage of orifices or even small-bore dosing lines; the supplier should be able to advise if this is a potential issue for any given product.

The extent to which a polyelectrolyte flocculant aid enhances settlement rate is influenced by the time delay between coagulant and polyelectrolyte dosing. The optimum delay time can be determined by jar tests, and will typically be of the order 2 to 5 minutes. Deviating from the optimum can have an appreciable effect. The optimum delay time is likely to be longer in cold water (<5 °C) than in warm, so there is a potential benefit to having some flexibility; it is generally simpler to provide alternative dosing points for flocculant aid than for coagulant. At an existing works the scope for changing the time delay may be limited, but it would nevertheless be instructive to determine how the actual delay compares with the optimum.

Site specific trial poly testing may be needed to match a suitable product to the specific raw water quality prevalent at the water treatment plant.

2.7 DOSING PUMPS

All automated coagulant dose control systems usually have separate control of coagulant and alkali (or acid) dosing for coagulation pH, such that dosing is automatically proportioned to works flow. The exception might be works which operate for long periods at constant flow, and where occasional manual adjustment of dosing in relation to works flow, would be feasible.

If fully automated control is to be implemented there may be a need to change existing dosing equipment. For example, if the existing dosing pumps cannot easily be adapted to provide works flow pacing (e.g. by changing pump frequency on diaphragm pumps) and changes to dose (by changing stroke length) then the pumps may need to be changed.

Pump replacement cost may be a significant element of implementing a fully automated system. Consideration should be given to future proof for automation requirements when specifying alum pump replacement.

2.8 KEY CONSIDERATIONS SUMMARISED

Coagulant should be dispersed rapidly (ideally in a few seconds) and effectively throughout the process flow. The effectiveness of dispersion is supported by dilution and application at a point of turbulence.

The order in which coagulant and pH adjustment chemical are added may impact on floc quality. In the case of low alkalinity waters, typical practice is to dose alkali before coagulant to avoid loss of alkalinity and ensure that the optimum coagulation pH is reached as rapidly as possible.

Flocculant aid (e.g. polyelectrolyte) should be dosed a few minutes after coagulant has been dispersed. There is benefit in having flexibility in the location of the flocculant aid dosing point: a longer delay between coagulant and polyelectrolyte dosing can be beneficial if water is cold.

Accurate pH measurement in waters of low ionic strength is supported by the use of sensors with a flowing reference junction, using sensors with a good track record in this application and ensuring that a good electrical earth is present in the system.

3. AUTOMATED CONTROL OF CHEMICAL COAGULANT DOSING

Automated control of chemical coagulant dosing has not been in widespread use in Ireland up to now with some notable exceptions in recent years (e.g. South Tipperary County Council). The types of automated chemical coagulant dosing systems can be divided into three main categories which are illustrated on Figure 3:

- **Feedforward** – based on the measurement of raw water quality, which is used to predict the required coagulant dose based on generic and/or "real" data for the water treatment plant using an algorithm to translate measurements of raw water quality into a coagulant dose.
- **Feedforward with feedback trim** – based on the same principles as the feedforward control but the system can include a secondary, automated feedback control loop based on the property of the floc soon after dosing or of the water quality after clarification/filtration.
- **Feedback** – based on the properties of the coagulated water shortly after coagulant dosing. The property of coagulated water generally used for feedback systems is a measure of surface electrical charge on floc particles known as "streaming current".

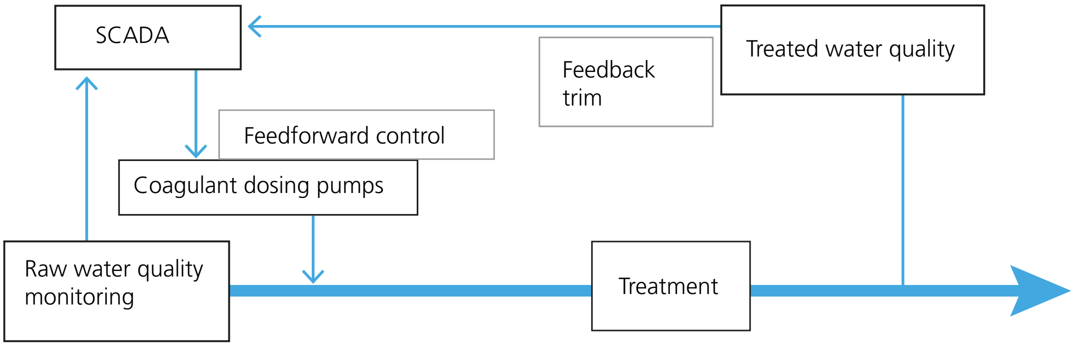

FIGURE 3. Overview of Coagulation Control Principles

3.1 FEEDFORWARD COAGULANT CONTROL SYSTEMS

3.1.1 SETTING UP A FEEDFORWARD COAGULANT CONTROL SYSTEM

Feedforward control is based on measurements of raw water quality, which are used to predict the required coagulant dose based on generic relationships and/or "real" data for the works.

The basic steps in setting up and operating a feedforward control system are as follows:

- Decide whether automated coagulant dose control is necessary. It is most appropriate for water sources that are subject to substantial and rapid variation in quality (e.g. direct abstraction from flashy rivers). If quality changes are gradual, manual control supported by existing dosing charts or tables with occasional jar testing may be sufficient. The latter is contingent on adequate cover at the plant to ensure that the dose can be adjusted in response to raw water variations before it has an impact on the final water quality.

- Decide which approach to feedforward control is likely to be the most appropriate. This includes deciding whether to go "in-house" and therefore develop and implement (including purchase of monitoring equipment) a dose control algorithm, or whether to consider the use of a specialist system supplier. "In-house" development may take longer but has the benefit of being less costly as well as leaving the user with greater knowledge and control if either difficulties arise or changes are needed.
- Collate existing raw water quality measurements and/or measure raw water quality. Corresponding data on works coagulant dose and/or jar test data are also needed, together with treated water quality data to show that the coagulant dose is appropriate. This is required to be carried out over an extended period to cover a suitable range of raw water quality (see Section 3). A chemical coagulant dosing system will only operate successfully if the quality and variations in the raw water have been properly characterised and assessed. This information is critical in the development of dosing regime or algorithm and is particularly important where dosing is automated.
- Develop an algorithm, or provide dose and water quality data to a supplier to develop/optimise an algorithm (see Section 3.1.3).
- Implement the algorithm into site control system and make necessary changes to dosing systems (e.g. enable automated control of pump delivery, provide on-line monitoring of coagulant flow).
- Operate the works manually by implementing the dose predicted by the control algorithm until confidence is gained by operating staff.
- Implement full automatic control under supervision.
- Reviewing the effectiveness of the automatic control periodically.

3.1.2 RAW WATER QUALITY MONITORING

The raw water quality parameters used for feedforward control depend on the nature of the water source, but usually include either colour or UV_{254} absorbance and turbidity. The suitability of a specific absorbance measurement is site dependent. Some systems measure absorbance at a single wavelength (e.g. 254 nm) while some scan across a range of wavelengths. More detail on raw water quality parameters is provided in Section 4.

Raw water quality monitoring systems can involve flow-through cells, which have cleaning and maintenance requirements, to measure absorbance of light. One system uses a simple "dip" probe which allows water to flow through a gap to measure absorbance, and potentially provides easier cleaning. The "dip" probe approach can also avoid the need for disposal of the sample stream.

UV or colour monitors may include correction for the impact of turbidity on absorbance measurement. This may be done either by provision of dual absorbance measurements or by "full spectrum" scanning instruments. Automatic correction for the impact of turbidity on absorbance measurements is preferred as it helps to ensure the accuracy of this feedforward control variable.

Pre-ozonation or pre-chlorination (dosing of ozone or chlorine to the raw water) would be expected to influence both natural organic load and corresponding measurements of absorbance. This could affect the accuracy of coagulant dose prediction at sites where dose is primarily determined by dissolved organic matter and ozone is dosed either intermittently or at varying dose.

3.1.3 FEEDFORWARD ALGORITHMS - GENERAL

A feedforward controller uses an algorithm (equation) to translate measurements of raw water quality into a coagulant dose. This may either be set up in-house or provided by a supplier of a proprietary system who will specify which quality parameters are used.

At its simplest the algorithm is a linear equation such as:

$\text{coagulant dose} = p_1 + p_2m_1 + p_3m_2 \ldots.$

Where coagulant dose is in suitable units (e.g. mg/l aluminium) and p_n are coefficients (i.e. numbers) and m_n are the relevant raw water measurements in appropriate units (e.g. turbidity, NTU).

Other forms of equation may be used which allow for non-linear responses. An on-line flowmeter is needed to measure the flow rate of coagulant at the point of delivery to the process. The coagulant dose calculated from this and the works flow should be compared with the dose predicted by the dose algorithm. A marked mis-match (e.g. 20%) would indicate a problem with the dosing system or its control and would raise an alarm. Typically flow is measured with electromagnetic meters, although mass flowmeters (coriolis type) provide similar performance with a larger bore, are markedly less sensitive to pulsing of flow and can provide density measurement which could be used to check product.

FEEDFORWARD ALGORITHMS - DEVELOP "IN-HOUSE" OR USE COMMERCIAL?

A treatment works should already have either a chart or table showing how coagulant dose varies as a function of one or more raw quality parameters. This is a guide for operators when setting dose, and constitutes, in effect, a manual feedforward control system. If the existing information covers an adequate range of raw water quality, it may either be used to support the development of a new in-house algorithm or to optimise a supplier-provided algorithm.

Commonly available software tools can be used to develop the dose control algorithms by users in-house, assuming that good coagulant dose data are available that cover an appropriate range of raw water quality.

For example, within MS Excel:

- the trend-line feature within the chart function allows single parameter relationships to be modelled as either linear or non-linear (e.g. polynomial) functions;
- the Regression function within the Data Analysis Toolpak, allows multi-parameter relationships to be modelled.

A simple example of the application of the MS Excel Regression function for the analysis of data is provided in Appendix B.

If a commercial control system supplier is used, the supplier will undertake the data analysis for the user who only has to provide the data requested. The data may be used to optimise a supplier's existing default algorithm, which the user may not have access to.

In-house or supplier-provided algorithms are eventually implemented for automated control at the works in question. This may either be by incorporation in an existing works SCADA system (if it has suitable functionality) or by provision of a separate control system. User-derived algorithms will employ proprietary monitoring instruments purchased by the user. Some suppliers can provide a complete service of setting up the feedforward control system, including data handling, setting up links to SCADA and commissioning.

3.1.4 MONITORING TO OPTIMISE CHEMICAL COAGULANT DOSING

This section reviews the water quality data that would need to be collected in order to allow development of an automated coagulant dosing system in particular feedforward coagulant control systems.

For water sources (e.g. impounding reservoirs) where raw water quality changes slowly, manual control of dose may be appropriate and cost-effective, and the algorithm may be used by operators to guide them to the correct dose. For sources subject to rapid change (e.g. direct abstraction from rivers) automated control may be appropriate, and the algorithm may be implemented to provide such control.

Whether water quality is measured continuously or manually is partly dependent on the parameter, as well as the potential rate of change in quality. Continuous monitoring allows for the provision of process alarms which can alert the operator to a significant deterioration in water quality. In the case of raw water, a continuous monitor can form part of a future implementation of automated feedforward dose control.

JAR TESTING

The feedforward equation used to control coagulant dose will only be as good as the accuracy of the information used to derive it. Unless very extensive jar test and associated raw water data are already available, regular, accurate, jar testing will probably be needed either during the development of a user-derived algorithm, or to support optimisation of a supplier's default algorithm.

Jar test data generally, but not always, provides a good guide to the dose required by the treatment process. In the specific case of dissolved air flotation (DAF) processes, the full scale process may operate satisfactorily with a different dose than that indicated by a settlement jar test. This may be due to the difference between the dose needed to produce a floc suited to settlement and the dose which will produce a floc suited to flotation, or may be due to features of the full scale process (e.g. turbulence close to the DAF nozzles) which are not replicated in the jar test. In this case it is recommended that settlement jar test data be collected but that the dose at full scale be modified by operator adjustment of the constant term in the feedforward equation based on clarified/filtered water quality.

PERIOD OF DATA GATHERING

Where users are developing their own automated dosing systems, the time period for collection of data should as far as practical be sufficient for all likely water quality conditions to be included. Thus, where surface water supplies are prone to rapid changes in quality (e.g. following heavy rainfall) the monitoring period should be sufficient to include such events. Also, where there are substantial seasonal changes in colour due to dissolved organic matter, the full extent of change should be covered. For some sites a full year's worth of data would be necessary, for others less prone to change, a shorter period may be adequate.

In the case of commercially available feedforward systems, it is clear that use of a supplier's default algorithm (with subsequent further, on-site, optimisation, as necessary) can substantially reduce the period of data required.

ABSORBANCE

UV absorbance or colour of the raw water are often the most critical parameters that must be measured in raw water. It is more appropriate that UV_{254} is measured rather than colour (at 400 nm) as:

- the absorbance spectrum of the humic/fulvic acids found in upland water climbs steadily in absorbance as wavelengths move towards UV, therefore measurement sensitivity is better at 254 nm than 400 nm;
- the aromatic double bonds (conjugated double bonds) present in natural organic matter that correlate with the potential for THM formation, absorb more strongly at 254 nm than 400 nm, thus reduction in THM formation potential is best accomplished by measuring UV.

UV_{254} absorbance can be divided by the dissolved organic carbon (DOC) concentration to give specific UV_{254} absorbance (SUVA). This is widely used to predict the potential for a natural water to form disinfection by-products (e.g. trihalomethanes, THM) during chlorination.

It is considered that the order of preference of options for measuring the concentration of dissolved organic carbon, which is linked to coagulant requirement, is as shown in Table 1.

TABLE 1. **Options for on-line monitoring of DOC by light absorbance**

Preference	Absorbance wavelength	Use in feedforward control
1	Scanning UV (e.g. 200 to 750 nm)	Most recent innovation, which purports to provide the best information on DOC concentration and type, and therefore coagulant requirement.
2	UV (254 nm)	Replaced colour from ca. 2000 onwards, particularly for upland waters.
3	Colour (400 nm)	"Traditional" approach

OTHER PARAMETERS

In addition to the raw water quality parameters that may be needed for the development of a coagulant dose equation, other measurements are needed to support the general operation of the works. Table 2 summarises all parameters for which monitoring is recommended, and why they should be monitored.

TABLE 2. **Raw water monitoring recommended frequency.**

Parameter	Why measure?	Type of measurement
UV absorbance	Most directly related to dissolved natural organic matter and therefore coagulant dose requirement. Surrogate for THM formation potential.	On-line if rapid change possible and automated system is required otherwise manual.
Colour	Alternative to UV, but may be less closely linked with coagulant dose.	On-line if rapid change possible and automated system is required, otherwise manual.
Turbidity	Related to coagulant dose requirement.	On-line
Temperature[1,2]	Affects ease of treatment, may also affect optimum coagulation pH.	Manual

Parameter	Why measure?	Type of measurement
Conductivity	Related to hardness of water, which affects ease of treatment.	Manual
pH and total alkalinity	Indicates pH buffering capacity and provides data relevant to design of pH control system.	Manual
Coagulant dose	Needed for future dose control. Indicates "load" on clarifiers and frequency of de-sludging.	Manual recording or SCADA data.

1 The viscosity of water increases by about 50% as temperature falls from 20 to 5 °C, so maximum upflow velocity in blanket clarifiers is lower in winter than in summer, and filter headloss is greater for a given filtration rate and bed state.

2 The efficiency of coagulation with metal ion coagulants declines as temperature decreases. There is some evidence that this impacts the performance of alum more than iron coagulants at very low temperature (< 5 °C) (Pontius, 1990). For aluminium coagulants, the optimum pH for coagulation is greater at lower temperatures (a decrease of ca. 0.4 pH units for a temperature rise from 2 to 20 °C); this effect is not seen with iron coagulants.

3 See EPA Advice Note No.4; Disinfection ByProducts in Drinking Water

Where a plant has been in operation for several years much of this data along with records of jar test and coagulant dosing records may already exist. Wherever possible such data and knowledge of the plant operation by the plant manager should be used to assist in the development of a chemical coagulant dosing system. Gaps in data may exist where UV absorbance /DOC is to be used to regulate automated dosing as this data may not have been routinely measured. Water suppliers should commence monitoring to fill such gaps.

FIGURE 4. DOC monitor

TREATED WATER PARAMETERS

Table 3 lists the treated water parameters that should be monitored to provide assurance that coagulation conditions are appropriate, and that other operating conditions for treatment are consistent with the production of satisfactory quality in the final water.

TABLE 3. **Treated water: monitoring recommended frequencies**

Parameter	Why measure?	Type of measurement
Raw water after coagulant (and associated alkali/acid) dosing		
pH value	Critical control parameter for coagulation.	Continuous
Clarified water (post-sedimentation)		
Turbidity	Performance of clarification and coagulation.	Continuous
Coagulant metal	Performance of clarification and coagulation.	Daily manual can be adequate.
Filtered water		
Colour or UV	Performance of coagulation	Daily manual can be adequate.
Turbidity	Performance of filtration and coagulation. Check for particulate breakthrough.	Continuous
Coagulant metal	Performance of coagulation	Manual can be adequate.

3.2 FEEDFORWARD COAGULANT CONTROL SYSTEMS WITH FEEDBACK TRIM

A feedforward dose control algorithm will not necessarily predict the correct coagulant dose under all raw water situations: for full optimisation a means of correcting the dose may be needed. Past experience of automated “trim” has not been positive and in general manual “trim” is used in practice. This may be due to the long time delay between when the dose is changed and when the system sees the result of a dose change which can lead to “hunting” (i.e. the dose automatically being adjusted up and down in search of the appropriate dose).

Filtrate turbidity can be used as feedback control as it is less vulnerable to being affected by operational changes and is very sensitive to changes in coagulant dose. For systems where a feedback trim is to be based on filtered water quality, the monitoring requirement is considerably more demanding as the turbidity level is so low, typically <0.1 NTU. As instruments have a poor response at this level, the specific model should be chosen with care, ideally based on a proven track record for this application. Such a trim can also be implemented manually.

Clarified water turbidity has been used to provide feedback trim for high rate clarification processes. Overall experience is that for conventional clarification processes (e.g. floc blanket clarifiers) the clarified water turbidity can be used as a guide to the appropriateness of coagulation conditions, but is not suitable for automated feedback trim.

Commercial systems measuring surface charge in the dosed water (i.e. between coagulation and clarification) have been used as a potentially rapid means of providing feedback. In principle this approach could overcome the individual limitations of each type of system.

In summary, feedforward coagulant control system can use automated feedback trim but in practice the "trim" aspect tends to be manually controlled due to the difficulties outlined above.

3.3 FEEDBACK COAGULANT CONTROL SYSTEMS

The most widely used system for feedback control of coagulant dose is based on a measurement - "streaming current" (SC) - that relates to the small electrical charge (the zeta potential) that resides on the surface of particles. The basic reason why SC (or other measures of particle charge) can be useful for monitoring and controlling coagulation, is that the addition of coagulants to water modifies particle charge, although the resultant charge is also dependent on coagulation pH and the ionic strength (as indicated by, e.g. conductivity or alkalinity) of the water. A schematic of a typical system is shown in Figure 5.

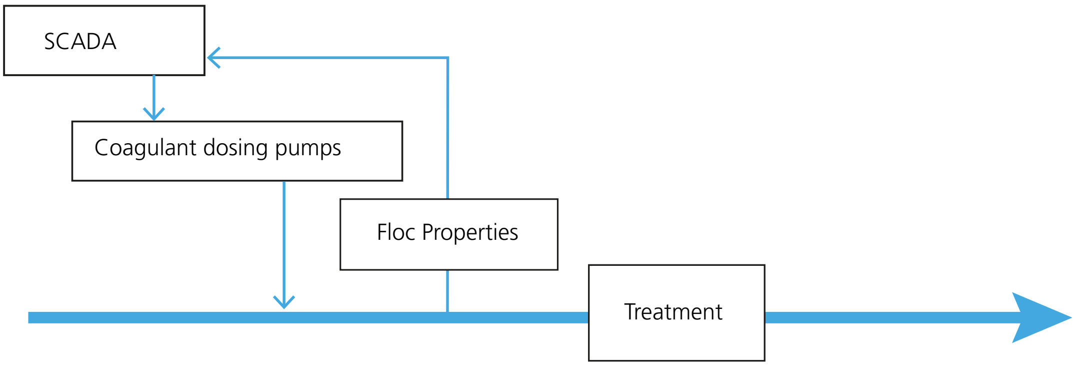

FIGURE 5. Feedback control based on properties of coagulant dosed water

The instrument that measures SC is referred to as a streaming current detector (SCD). The SCD is fed continuously with a sample of water taken shortly (typically 2 to 5 minutes) after coagulant addition and dispersion.

A suitable coagulated water sample stream is needed, taken from either the coagulant mixer or coagulated water stream shortly after dosing. Because SC is sensitive to process factors such as effectiveness of coagulant dispersion and changes in coagulation pH, commissioning can be time consuming depending on the degree to which an existing coagulation process is optimised, and the flexibility of options for sampling.

Suppliers will set up and operate the SC system so as to control coagulant dosing to maintain a target value for SC. Although no specific raw water data are needed by the supplier, the more variable the water quality, the greater the difficulty in maintaining a single target value for streaming current.

The SCD requires periodic cleaning, with frequency dependent on local conditions.

3.3.1 SETTING UP A FEEDBACK CONTROL SYSTEM

The basic steps in setting up and operating a Streaming Current Monitor (SCM) feedback control system are as follows:

1. The SCM will require, as a minimum, electrical power, a sample of water post coagulant dosing, a waste outlet and a connection to the alum dosing pumps.

2. Very careful selection of the sample point and sample delivery method is necessary. This is because the charge and streaming current generated in the sample changes over a short period of time. Therefore the sample location chosen must be close to the coagulant dosing point at a point where the coagulant and water are well mixed. A method to measure chemical dispersion is given in Appendix A.

3. The sample delivery system must deliver the mixed sample reliably to the SCM, with a variability of no more than +/- 10% of the initial rate, over all normal plant operating conditions. There should be as short as possible lag time (max 3 minutes) between sampling and delivery to the SC measurement cell. When designing the sample line system, consideration should be given to providing a clean water flushing capability. A flow alarm on the sample line is also recommended.

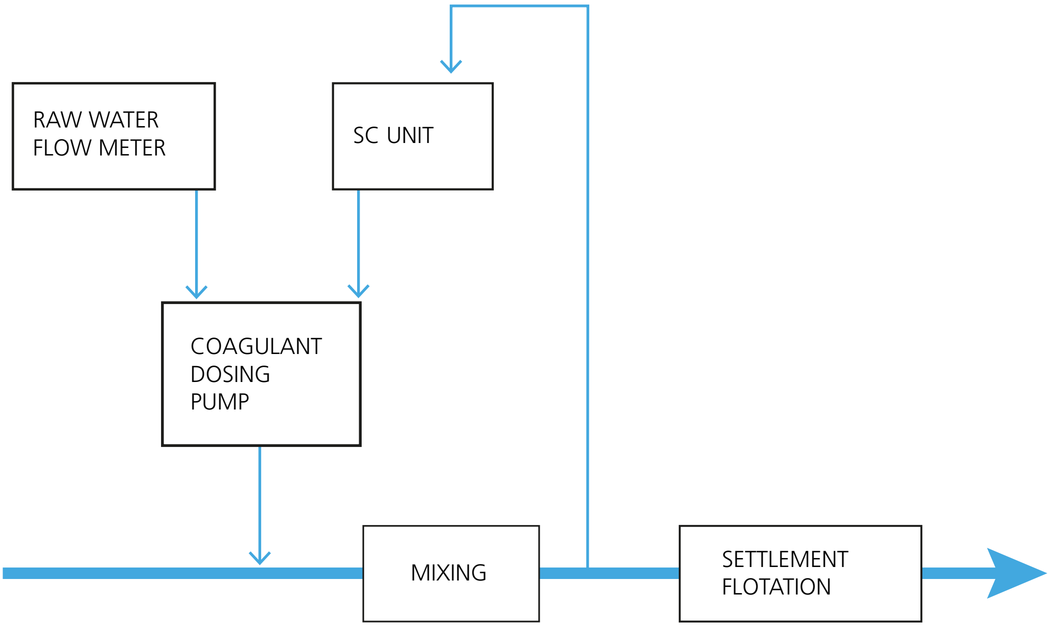

FIGURE 6. **Feedback control of coagulant pump based on properties of coagulant-dosed water**

4. The optimum coagulation dose should be set using classical methods, such as jar tests and settling tank observations. Raw water flow and quality, and coagulant dosage conditions should be kept steady during initial setup of the SC controller.

5. Once steady and satisfactory raw water and coagulation conditions are observed then the streaming current charge is noted. It is recommended to adjust the signal gain control on the SC unit so as to set the signal display to give a reasonable deviation of signal (usually 0 +/- 30) over normal operating conditions. A steady signal from the SCM should be observable at this stage and the SCM setpoint should be now selected corresponding with the optimum coagulation conditions at the plant.

6. The SCM should be operated for a few days in manual control to observe how it operates under normal process operation.

7. Frequent monitoring is advised in the first few days of using the system until confidence is gained in the setpoint chosen and the control of dosing. Re-adjustment of the setpoint may be required during this phase.

8. Following set-up and commissioning, the SC system should cope with normal changes in multi-source blends and changes due to weather conditions, but it may need to be adjusted occasionally, particularly if a major change in raw water source(s) occurs or there are changes due to seasonal factors, e.g. algal blooms in lake sources.

9. Service requirements are usually daily or weekly manual cleaning or else automatic flushing of the measurement cell and annual service of instrument by equipment supplier.

DOSING PUMP CONTROL FOR FEEDBACK SYSTEMS:

It's imperative that some thought be put into the pump selection process.

Ideally the pump should have speed control and also have electrically actuated stroke control based on a 4-20 mA signal from the SC controller.

The pump capacity will generally be sized 4 times the normal requirement. This is on the basis that the plant flow meter is operating mid range and the desired operating point for the pump stroke is 50% i.e. within the linear region.

PUMP MOTOR ISSUES:

Ideally the pump will have additional forced ventilation where a 20:1 turndown on speed can be achieved proportional to the raw water flow signal.

Ensure the motor has 230/380 voltage selection as this will allow the use of a speed controller with single phase input should the plant only have a single phase supply.

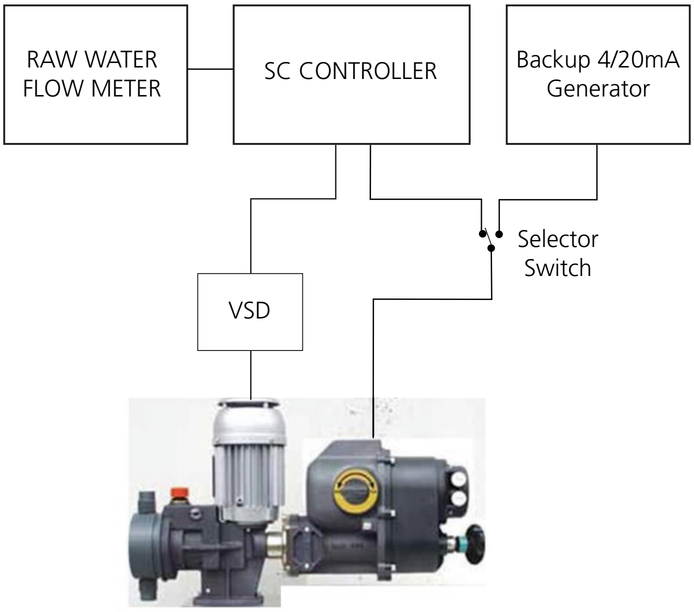

FIGURE 7. SCM Dosing Pump Control

FAIL SAFE:

As with all systems, consideration should be given to procedures in the case of problems with equipment. In the case of SCMs the following 'fail-safe' precautions are advised:

Note not all commercially available SCM systems have these capabilities

- Programme an upper and lower limit on the control from the SCM to avoid significant under and over dosing should a problem with the SCM system arise.
- Programme the SCM unit to revert to a default coagulant pump control signal should a problem with the sample flow of SCM arise.
- Whether the stroke control signal is derived from a SCADA system or the SC controller, a manual backup is recommended. A selector switch should be installed which could select the manual stroke control signal derived from a back-up graduated potentiometric 4/20 mA generator.

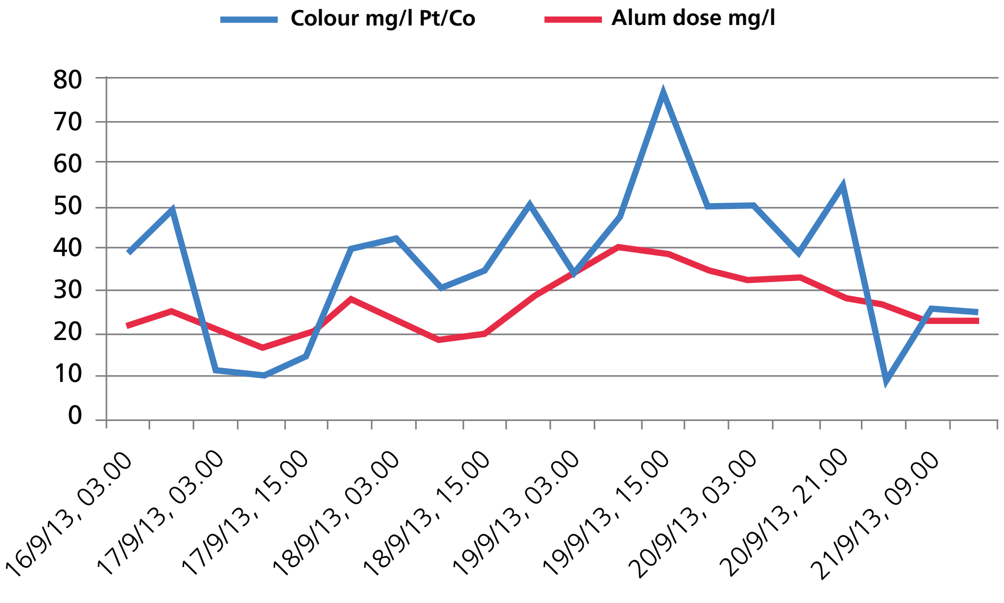

FIGURE 8. Typical Aluminium Sulphate Dose Control Using SC

4. SUMMARY OF THE ADVANTAGES/DISADVANTAGES OF FEEDFORWARD AND FEEDBACK CONTROL SYSTEMS

This section provides a summary of the main advantages of the feedforward and feedback control systems. This information was collated following consultation with suppliers currently using such systems as part of the WRc review of chemical coagulant dosing commissioned by the EPA.

4.1 FEEDFORWARD

ADVANTAGES

- Can be used in all clarification processes and water types.
- Once a suitable algorithm has been derived, it can provide very responsive control over a wide range, and rate of change, of raw water conditions.
- Provides sensitivity to changes in alkalinity, retention time, mixing conditions and pH.
- Can control pH as well as chemical coagulant dose.
- Can target specific treatment requirements such as THM based on specific absorbance at specific wavelengths or filter run length.
- A commercial feedforward system may be optimised more quickly than a new, user-developed system, as the supplier's default algorithm can allow control to be implemented more quickly than a user-developed system.
- In house developed feedforward system are less costly and user has greater knowledge and control if difficulties arise or changes are needed.

The estimated costs of the feedforward control systems in use by suppliers consulted during the review were €20-60,000.

DISADVANTAGES

- Requires prior collection of raw water data covering the range of water quality in conjunction with extensive jar testing. This can take several months.
- Commercial systems can be expensive, such that they may only be justifiable on the larger works.
- For commercial systems, the algorithm may not be known to, nor be modifiable by, the user. If modification is needed, this would be at additional cost.
- The operation of the necessary water quality monitors will necessitate ongoing maintenance and calibration.

4.2 FEEDBACK USING STREAMING CURRENT

ADVANTAGES

- Can in principle be commissioned quickly if the existing coagulation process is optimised and options for sampling are available.
- Most suitable where variations in raw water quality are small and gradual.
- Responds quickly to a change in coagulation conditions and can therefore provide early warning via alarm that coagulation is incorrectly set.

The estimated costs of the feedback control systems in use by suppliers consulted during the review were €15-20,000.

DISADVANTAGES

- The controlled variable (streaming current) responds to several variables, so it may therefore not provide acceptable control on water sources that are highly variable.
- Following set-up and commissioning the SC system may need to be adjusted occasionally, particularly if a major change in raw water source(s) occurs or there are changes due to seasonal factors e.g. algal blooms.
- The link between the SC and water quality may vary and this link is not always clear to operators.
- May require weekly calibration using off-line measures of zeta potential.

4.3 GENERAL CONSIDERATIONS

ALL SYSTEMS

1. Selection of the appropriate technology and extent of investment will depend on the information collated, how substantial and rapid the variation in water quality is and adequacy of existing controls, i.e. extent of plant cover.

2. Separate control of coagulation pH by alkali dosing will usually be needed with low alkalinity waters to ensure that the optimal coagulation pH is maintained during changes to raw water quality and coagulant dose.

FEEDFORWARD CONTROL

1. A feedforward controller uses an algorithm (equation) to translate measurements of raw water quality into a coagulant dose. This may either be set up in-house or provided by a supplier of a proprietary system who will specify which quality parameters are used.

2. The dosing system will only be as good as the accuracy of the information used to set it up. The quality and variations in the raw water is required to be properly characterised and assessed in conjunction with establishing the appropriate coagulant dose.

3. Dosing pumps may need to be modified or changed such that dosing rate can be controlled in proportion to works flow, as well as in relation to the dose predicted by the algorithm. The flowrate of coagulant will need to be measured on-line to verify that the correct dose is being applied.

4. For user-developed algorithms, raw water quality data needs to be collected over a long period (up to a year) to cover most source water conditions. Corresponding data on works coagulant dose and/or jar test data are also needed, together with treated water quality data, to show that the coagulant dose was appropriate. Water quality data can either be collected automatically - provided suitable on-line monitors are available (e.g. colour, turbidity, UV_{254} absorbance, pH) - or frequent manual samples can be taken.

5. Suppliers of commercial systems may install their own raw water monitors prior to implementing control. They will collect the raw water data needed by their systems as well as treated water and dose data from the site in question (as per 1.) and use this to optimise their algorithm. The data collection period should be shorter (e.g. 3 months) than for a user-developed system, as suppliers can provide a default algorithm as a starting point.

6. Appropriate sampling would need to be in place, such that if the raw water quality varies quickly, there is no significant delay in measurement and subsequent control of coagulant dose.

7. Systems are usually set up such that the feedforward predicted dose can either be adjusted manually or the system changed to full manual control.

8. Raw water monitors need to be calibrated and maintained so that they provide accurate information. A "dip" type probe can be easier to clean and can avoid the need to dispose of the sample stream.

9. Alarms indicating low flows to an instrument and alarms indicating dosing problems are important to alert to potential problems.

10. Optimal Coagulation pH is a critical control parameter. Regulation can be achieved by incrementally increasing soda ash bands based on DOC where control loop problems arise.

11. Treated water parameters should be monitored to provide assurance that coagulation conditions are appropriate, and that other operating conditions for treatment are consistent with the production of satisfactory quality in the final water.

APPENDIX A ASSESSING CHEMICAL DISPERSION

GENERAL

The Coefficient of Variation (CoV) of a chemical concentration can be used to assess dispersion. It is a measure of the homogeneity of radial mixing achieved in a pipe or channel. Samples are taken at a point downstream of dosing and analysed for the dosed chemical. CoV is defined as:

$$CoV = \frac{\delta}{\chi}$$

where δ = standard deviation

$\bar{\chi}$ = arithmetic mean concentration

$$\delta = \sqrt{\frac{\sum_{i=1}^{n} (\chi_i - \bar{\chi})^2}{n - 1}}$$

n = number of samples

CoV as defined above is a fraction, but is often expressed as a percentage (e.g. CoV = 0.05 = 5%). It is a measure of the degree of scatter of sample values relative to the mean of those values. A smaller CoV signifies less scatter, which in this context equates to better mixing of a chemical. Assuming that the samples follow a normal distribution, about 95.5% of sample values will lie within the range of ± *2 CoV* of the mean.

For coagulant, a CoV of 5% or less, a few seconds downstream of dosing is considered acceptable. It means that about 95.5% of concentration measurements will lie with ±10% of the mean. A CoV of > 10% would indicate scope for improvement.

METHOD

Ten samples are generally used for this assessment, taken at a single point downstream of dosing. The main objective is to take all the samples as quickly as possible. Sample volume should be as small as practical (e.g. 25 ml bottles) to minimise any smoothing of the variation in concentration that might occur over the time taken to fill the sample container.

Variability arising from the analytical method is included in the measurement of CoV and can be substantial, particularly if portable test kits (e.g. Palintest, Hach) are used. The analytical CoV should therefore also be determined, by taking a bulk sample, ensuring it is well mixed, and then analysing 10 sub-samples.

The analytical CoV increases as the limit of detection of the analytical method is approached, which may influence how samples are prepared. Analytical CoVs from standard methods of laboratory analysis would be expected to be lower than those from test kits. The analytical CoV should be subtracted from the sampling CoV to assess the true variation in the process.

APPENDIX B DERIVING A FEEDFORWARD EQUATION FROM JAR TEST DATA

GENERAL

Jar test (or works data) for coagulant dose and raw water quality can be used to derive an equation or algorithm linking dose to one or more raw water quality parameters. Note: the data must relate to conditions known to provide effective coagulation on the full scale process or an unreliable algorithm will be derived.

EXAMPLE: LINEAR RELATIONSHIP BETWEEN DOSE, COLOUR AND TURBIDITY

Table B1 provides an example data set for optimum coagulant dose, raw water colour and turbidity.

TABLE B1 Simulated jar test results for coagulant dose, colour and turbidity

Coagulant dose (as mg/l $Al_2(SO_4)_3$)	Colour (as degrees Hazen)	Turbidity (as FTU)
1	8	10
0.8	5	5
1.3	15	5
1.2	13	5
1	7	15
2	29	5
2	27	15

Application of the MS Excel Regression function (available with the Excel Data Analysis Toolpak) to the data yields a summary output from which the following information is taken:

X Variable 1 (i.e. colour) = 0.05

X Variable 2 (i.e. turbidity) = 0.01

Intercept (i.e. constant) = 0.5

The regression statistics in this case show a perfect correlation ($R^2 = 1$), and the predictive equation is:

Coagulant dose (mg/L Al) = 0.050*Colour(Hazen) + 0.01*Turbidity(FTU) + 0.50

If Excel trendline linear analysis is applied to a chart of dose and colour only (i.e. turbidity is excluded), an almost equally good equation is derived, confirming that turbidity has little influence under the conditions evaluated, and a simplified equation may be acceptable at the site in question:

Coagulant dose (mg/L Al) = 0.050*Colour(Hazen) + 0.58
$R^2 = 0.99$.

In this case the data set is small and it would be prudent to examine a wider set of data before proceeding with a simplified equation (and therefore simplified control system).

Note: R^2 gives a measure of the reliability of the linear relationship between the x and y values. Values close to 1 indicate excellent linear reliability.

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