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Coagulant-based emergency water treatment

C.C. Dorea

Department of Civil Engineering, University of Glasgow, Rankine Building, Oakfield Ave., Glasgow G12 8LT, United Kingdom
Tel. ++44(0) 141 330 6458; Fax ++44(0) 141 330 4557; email: caetanodorea@hotmail.com, dorea@civil.gla.ac.uk

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Abstract

Emergency water treatment approaches relying on coagulation vary from centralised modular and portable ''kits'' to ''point-of-use'' or ''household'' interventions. Typical coagulation practice in emergencies is reviewed in view of field constraints (e.g. equipment and resources) and contrasted with underlying theory and conventional water treatment procedures. Examples of coagulation in emergencies are also presented based on documented field experiences alongside the discussion of other relevant issues such as process control, sludge production and management, ease of use, and aluminium coagulant residuals in finished waters.

Keywords: Aluminium sulfate; Coagulation; Disaster; Emergency; Flocculation; Water treatment

1. Introduction

An emergency is a ''situation arising in the aftermath of a disaster'', which can result in ''a serious disruption of society, involving widespread human suffering and physical loss or damage, and stretches the community's normal coping mechanisms to a breaking point'' [1]. Emergency relief efforts from aid organisations are necessary when the response capacity of local authorities is insufficient. From a public health point of view the (re-)establishment of a safe water supply is one of the three main interventions, together with hygiene promotion and sanitation. Such actions will reduce the exposure of the affected population to health risks and prevent the spread of water- and excreta-related diseases, as classified by Mara and Feachem [2].

The transmission of water-related diseases in emergencies is as much likely to the lack of sufficient quantities for personal and domestic hygiene as to contaminated water sources [3]. Hence, the quantity of water supplied is prioritised over the quality [4]. However, this is done without neglecting the importance of a supply that is free of pathogens and aesthetically pleasing. In other words, according to Luff [5], ''a larger quantity of relatively good quality water is better than a small quantity of very high quality water''. Minimum levels of water quantity and quality in a humanitarian response (Table 1) have been proposed [3]. Water quality should always be improved, but it does not change as much as the quantity requirements. That is, as emergencies shift from immediate-,

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Table 1
Selected sphere standards water supply [3].

Standard	Key indicators (abridged)
1 – Access and water quantity	• On average at least 15 L/head/day for drinking, cooking and personal hygiene • Maximum distance to the nearest water point from the household is 500 m • Queuing time at a water source is less than 15 min • No more than 3 min to fill a 20 L container • Water sources and systems are maintained, delivering adequate quantities on a consistent or regular basis
2 – Water quality	• A sanitary survey indicates a low risk of faecal pollution • No faecal coliforms per 100 mL at the point of delivery • Protected or treated source used in preference to other available sources • Steps are taken to minimise post-delivery contamination • Disinfection with free Cl_2 residual at tap of 0.5 mg/L and turbidity <5 NTU • No negative health effect is detected due to short-term use of water contaminated by chemical (including treatment chemicals) or radiological sources, and assessment shows no significant probability of such an effect

late-, and post-emergency phase, water quantities also change. Initially, water supply ensures the survival of the victims catering their very basic needs. As water sources are developed, larger volumes can be supplied for other purposes (e.g. bathing, laundry, and livestock). Finally, more durable/sustainable water supplies are sought during the rehabilitation work involved in post-emergency relief.

When surface waters are used as emergency sources they must undergo treatment which essentially involves turbidity reduction to facilitate disinfection; typically achieved by coagulation. Although it is relatively well established as a treatment process for conventional municipal drinking water purification plants, its use in emergencies must be adapted due to practical constraints (e.g. instrumentation and resources). This paper provides an overview of coagulation as an emergency treatment process in view of current practice and other issues arising from field experience and discussions within humanitarian aid agencies, such as coagulant residuals and sludge disposal.

2. Coagulation

Conventional water purification plants utilise coagulants primarily for turbidity reductions and removal of natural organic matter. The latter are removed as precursors to potentially carcinogenic disinfection by-products. Furthermore, coagulants are capable of achieving a considerable reduction of microbiological contamination. Yet, in emergencies, coagulants are used primarily for the reduction of turbidity and to facilitate chlorination. This is due to the minimum emergency water quality requirements (Table 1) and to the basic analytical field capacity available in emergencies, such as ''DelAgua kits'' [6]. Such water quality testing kits are capable of making determinations of four critical drinking water quality parameters: thermotolerant (faecal) coliforms, turbidity, pH, and free/total residual chlorine. As such, any additional contaminant removal that may occur comes as a secondary benefit, as they cannot be measured.

Aluminium sulfate, or alum, is the most common coagulant used in emergencies, as it can be procured locally at a relatively cheap price in most parts of the world. Optimum turbidity reductions with aluminium sulfate can normally achieved within the pH range of 6.0–7.5 [7]. The minimum solubility of aluminium (Fig. 1) usually lies within this range (i.e. pH 6.0–7.0) [8], which is important to consider during the control of aluminium residuals. When alum is added to

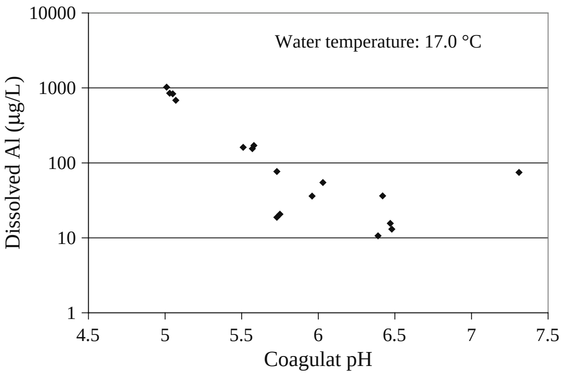

Fig. 1. Minimum solubility of aluminium between pH 6.0 and 7.0 (experimental data from Berube and Dorea [8]).

Fig. 2. Batch coagulation tanks used in Gahri Doppata (Pakistan).

aqueous solutions it undergoes hydrolysis, thereby releasing hydrogen ions. This can cause the depression of pH if sufficient alkalinity buffering is not available. Another factor to consider when using alum is that its performance may be hindered at low temperatures (i.e. <5°C) which causes reduced turbidity reduction efficiencies and possibly high Al residuals in the finished water [9–11]. These residuals are deemed unwanted and are discussed later in this review.

Other coagulants include ferric salts (e.g. ferric chloride and ferric sulfate), polyaluminium chloride, and polyelectrolytes. With the exception of ferric chloride, which is used by Médecins Sans Frontières [12], none of these coagulants are routinely used in emergencies. For that particular aid agency, the choice of ferric chloride over alum is based on its wider ''usable'' pH range of 5.0–9.0 and its ease to dissolve. However, it is recognised that ferric chloride can be difficult to source in the field and can result in finished water with a ''yellowish'' appearance. Some of the other coagulants are only available in liquid form and may be classified as ''dangerous good'' for transportation purposes. Other factors that preclude the use of these other coagulants in emergencies may include their price, level of skill and equipment necessary for process control, and local availability for initial stock replenishment.

3. Current practice in emergencies

Most modular, mobile and household particle separation processes for emergency water treatment rely on coagulants; these different treatment approaches are reviewed in greater detail elsewhere [13]. Modular treatment systems are those which are assembled on site. Mobile units are typically mounted on to a self-contained trailer or portable container. Point-of-use treatment consists of ''household'' level water treatment interventions.

Batch coagulation is a modular approach and is also the most common and simplest form of emergency water treatment. This is carried out by adding the coagulant stock solution to the incoming water flowing into large modular storage tanks. It is common to find tanks comprised of corrugated steel sheets that bolted together form a circular tank of 11, 45, 70 or 90 m^3 (Fig. 2); within these circular structures a synthetic butyl rubber liner is fitted. Once the coagulant is added and the tank is full, the water is left to settle (for up to 12 h). After which it is decanted, stored, and disinfected prior to distribution. The occurrence of scum and the carryover of settled floc are two operational problems that can affect water quality during batch coagulation. Simple improvements using locally available materials to construct an overflow scum collector and floating tank outlet can be used to overcome such difficulties and improve water quality [14].

Other coagulant-based approaches include systems based on up-flow blanket clarification and with pressure filtration units. These add another dimension of complexity in comparison to the simplicity of batch treatment, but are proven to be effective in

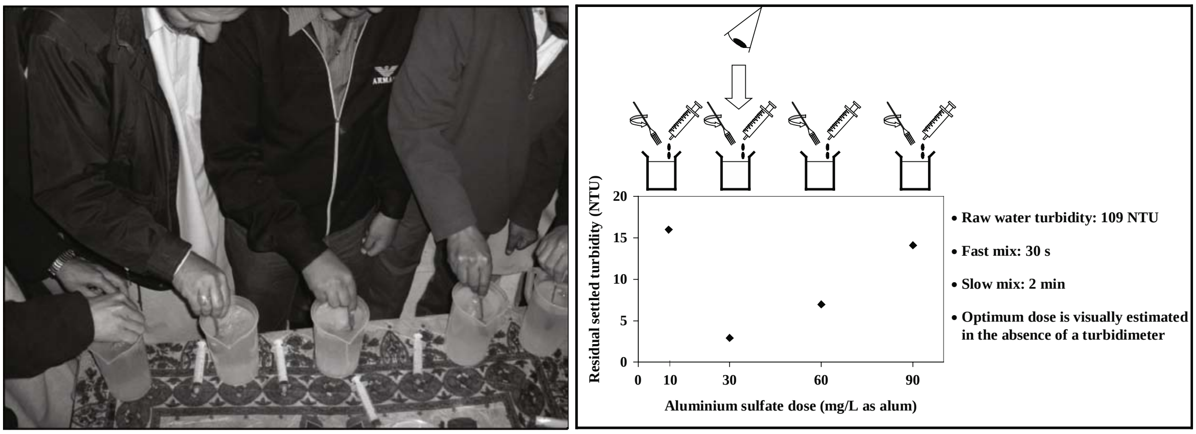

Fig. 3. Simplified jar-test field procedure for coagulant dose determination.

emergencies [12,15,16]. In non-emergency situations, point-of-use options, some of which utilise coagulants (mainly ferric salts), are a more effective water treatment intervention to reducing diarrhoeal diseases in comparison to treating water at source [17]. However, it may be difficult to implement a point-of-use water treatment strategy during the first phases of an emergency due to its logistical requirements (i.e. necessary training and distribution of water quality improvement items) [13]. Such difficulties were reported in the initial phases of the Indian Ocean tsunami emergency response when the implementation of some point-of-use water treatment activities were attempted [18].

3.1. Coagulant dose determination (field jar-test)

In conventional water treatment practice coagulant doses are typically determined by empirical experiments that are better known as ''jar-tests'' [19]. During emergencies jar-testing has had to be modified due to the unavailability of conventional jar-testing equipment (e.g. jar-testing apparatus, turbidimeter, and volumetric pipettes). Field jar-tests are improvised with locally available materials such as forks or wrenches, serving as stirrers, and syringes, for applying the coagulant into plastic beakers. Increasing coagulant doses are applied to each beaker; which are typically stirred vigorously for 1 min (i.e. fast mixing), followed by 2–3 min of gentle/slow mixing and then left to settle for 20–30 min (Fig. 3). Normally, as turbidimeter is not available, the ''optimum'' dose is estimated by visual inspection of the beakers and selection of the ''clearest'' beaker. Experience from the Asian tsunami has shown that basic training in jar-testing can be easily and successfully assimilated by relatively unskilled operators. This was noted in a visit to a up-flow clarification unit that had been running for more than 2 years by operators that received jar-testing training [16].

The reduced times, compared to conventional jar-tests, are due to the fact that the whole procedure is manual and may need to be repeated several times; in such cases it is important that mixing times and intensities are as consistent as possible between tests. However, it is recognised that the rationale of the jar-test is to reproduce the mixing times and velocity gradients of the relevant unit processes. This is not achieved with the simplified jar-test. As such, the optimum dose is considered to be only an estimate; which is based on the best possible systematised methodology that can be applied considering working conditions and resources available during emergencies. In addition, as opposed to conventional jar-test practice, optimum coagulation pH is usually not determined with field jar-tests. Acid solutions would be used in order to depress the pH. However, the transport and handling of concentrated acid solutions is perhaps too hazardous in emergency settings. Adjustment of the coagulation pH to more alkaline values would be possible with sodium hydroxide or lime, as it can be locally sourced and is available in solid form with facilitates its transportation and handling. With respect to this it must be borne in mind that emergency operations usually rely

Fig. 4. Different suction side doser configurations as used by MSF (left) [12] and Oxfam (right) [16].

on local (many times unskilled) labour for the daily operation of water treatment facilities.

3.2. Coagulant dosing

The aluminium sulfate can be applied to the main flow of water into the tanks as a liquid solution or in its solid form. When aluminium sulfate is supplied in granular form, it can be easily dissolved to prepare a coagulant stock solution, which can dosed and applied to the main flow of water by constant or near constant pouring (or dripping with a doser) or by what is known as a ‘‘suction side doser’’. The latter form of dosing liquid solutions was originally developed by Médicins Sans Frontières and has found application in different modular treatment approaches [12,15,16]. It consists of a small diameter pipe tapping on to a pump’s suction line (Fig. 4) with a valve to control the dosing rate. The pump’s suction is used to draw the coagulant from a vessel. Mixing is provided by the pump impeller and in the pumping lines. As the level in the stock solution container drops, the dosing flow rate decreases and must be adjusted, so as to maintain a constant dosing.

When aluminium sulfate is supplied in crystal or in rock form, it will require more time and mixing to dissolve. This inconvenience can be overcome by making an ‘‘alum cage’’ [14], which is a basket made with chicken wire mesh and wooden posts (Fig. 5). This alum cage is then secured to the tank’s inlet pipe and the pre-determined amount of ‘‘rock alum’’ requirement for the tank is added to the cage as the tank is being filled. Such a dosing arrangement can overcome two problems: the need to dissolve the alum and the need for a stock solution doser.

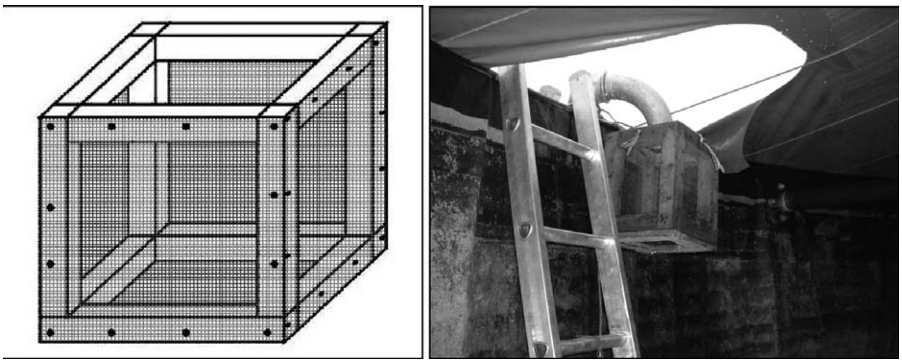

Fig. 5. ‘‘Alum cage’’ placed at tank inlet for rock alum dissolution used in Pakistan [14].

4. Coagulant residuals

Use of aluminium sulfate may leave a coagulant (aluminium) residual in the finished water. These are unwanted and should be minimised, as they can cause problems in water distribution systems and during disinfection [20]. During conventional water treatment, properly operated and maintained aluminium sulfate coagulation processes should not experience problems with high aluminium residual levels [21]. Increased concentrations of aluminium in finished waters may be either due to problems associated with its solubility at low pH or to low temperatures. Low coagulant residuals are also warranted as a precautionary approach to the unknown health effects of drinking water Al exposure. It has been hypothesised that there is a link between drinking water aluminium and the onset of neurodegenerative diseases, such as Alzheimer's disease [22]. However, to date no real association between drinking water aluminium and Alzheimer's disease has been established. Epidemiological studies have yielded inconclusive and/or contradictory results. As such, current World Health Organisation guidelines [21] for aluminium in drinking water (<0.2 mg/L) are due to aesthetic considerations (i.e. elevated aluminium levels may cause high turbidity) and not health-based.

During emergency water treatment operations, aluminium residuals are not routinely monitored. Rather high final aluminium levels of just below and over 0.200 mg/L have been reported [23,24]. These studies were on up-flow clarifiers and utilised spectrophotometric and other colourimetric methods for the aluminium determinations, which are not usually found during emergencies. Colour comparators, such as those used for free chlorine and pH measurements, are a simpler alternative to the spectrophotometric methods. However, during the measurement of aluminium it must be born in mind that it can be subject to interference from several sources [25], such as: phosphates, fluoride, iron, manganese, alkalinity, and aluminium itself, being one of the most ubiquitous elements in nature.

In order to control aluminium residuals from coagulation, it is first of all necessary to verify whether the measured metal concentration is of particulate or dissolved origin. The dissolved fraction can be determined by filtering the sample through a 0.45 μm ''pore-size'' membrane, such as those used in the detection of thermotolerant (faecal) coliforms. The particulate aluminium is calculated as the difference between the total (unfiltered) and dissolved (filtered) aluminium. pH and turbidity measurements should be done on the original (unfiltered) sample. Particulate aluminium can usually be correlated with turbidity [26]. In such cases, improvements in settling conditions through coagulation optimisation or by simple process upgrades to prevent carryover flocs from settling tanks [14] can aid in reducing the turbidity-causing particulate aluminium. High dissolved aluminium is usually associated with pH below 6.0 due to its increased solubility at lower pH values (Fig. 1). Increasing the *coagulation pH* by lime or sodium hydroxide addition to the 6.0–7.0 (i.e. minimum solubility) range could aid in reducing the dissolved residual levels [27]. That is, the lime or sodium hydroxide should be added to the water before the dosing of the coagulant to result in a (final) coagulation pH between 6.0 and 7.0. However, the any dissolved aluminium residual reducing strategy must not jeopardise the turbidity reduction efficiency of the coagulation, as this may affect the disinfection process and can make the finished water less aesthetically appealing.

5. Sludge disposal

Sludge is the by-product of the water purification process by coagulation, consisting mainly of aluminium hydroxide, pathogens and the organic and inorganic substances removed by the aluminium sulfate. During conventional treatment the sludges are usually treated and conditioned prior to disposal in sewers, landfills or application to land, all of which account for the majority of the residual waste produced [28]. During the 1970s, the most practiced disposal method in the USA was discharge without treatment into watercourses, this practice now only accounts for 11% of the residual water treatment waste produced [28].

Common practice in emergencies is to dispose of the sludge into watercourses. This practice may be considered undesirable from an environmental point of view, due to the high aluminium concentration in the sludge; which can have a toxic effect on the aquatic ecosystem. However, it may be the only viable alternative, as there may be limitations on staffing and resources to treat and condition the sludge. In such cases care should be taken that the sludge is disposed of at a point downstream of the treatment plant intake.

6. Discussion

There are many contrasts between conventional coagulation practice in municipal water treatment plants and use of coagulants (mainly aluminium sulfate) in humanitarian emergencies. Circumstantial constraints dictate different water supply and treatment objectives. Furthermore, limitations on available equipment and resources, lead to the adaptation of techniques and simplifications of water treatment procedures (e.g. jar-testing and coagulant dosing). From a conventional water treatment perspective, coagulation practices in emergencies are oversimplifications and would not be acceptable in well-regulated water purification plants. Yet, they have been applied successfully in emergency contexts.

More advanced treatment technologies, such as sand and membrane filtration systems, are improving in their adaptability to humanitarian crisis scenarios. However, many of these systems are not tolerant of high turbidity (suspended solids) levels frequently encountered in the field [13]. Filtration systems in general, are more effective with low turbidities that can be achieved with adequate pre-treatment with coagulants. As such, an eventual shift to more sophisticated methods of emergency water treatment is still likely to hold the coagulation stage as a vital requirement to a successful operation. However, increasing degrees of complexity of the purification systems must be accompanied by adequate operator training.

Given its many advantages and successful applications, it seems rather unfortunate that unwarranted ‘‘fear’’ is sometimes associated with aluminium sulfate; in particular with reference to (unestablished) health risks. The use of alternative coagulants to aluminium sulfate is sometimes justified on the basis of the postulated *long-term* health risks possibly associated with aluminium in drinking water, *e.g.* Alzheimer's disease. It must be noted that to date, there is no conclusive evidence to support a health-based guideline for aluminium in drinking water [21]. Furthermore, given the relatively short duration of emergency responses a *long-term* exposure is unlikely to occur. In order to ensure a more sustainable water supply operation, chronic emergencies should look into shifting towards water treatment processes that have a minimal reliance on chemical supplies (e.g. slow sand filtration) [13]. Nonetheless, if conditions permit, aluminium residuals should be minimised on the basis of the precautionary principle and of good practice, as low metal residuals are a sign of well operated coagulation-based systems [21].

7. Conclusion

Coagulation with aluminium sulfate has been and is likely to continue to be a key process in successful emergency water treatment and supply operations. This is due to its many advantages that include: wide local availability of aluminium sulfate; relative ease of transport, adaptability to local conditions (i.e. used with local materials and resources), and ease of assimilation by (unskilled) operators with training.

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