



Conventional, Enhanced, and Alkaline Coagulation for Hard Ghrib Dam (Algeria) Water

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Abstract: This work aims to study coagulation process for hard Ghrib Dam (GD) water treatment. Conventional coagulation (CC), enhanced coagulation (EC) and alkaline coagulation (AC) experiments were realized on jar tests. This study demonstrated the effectiveness of GD water treatment by the EC process compared to CC. Indeed, by CC, it has been demonstrated that each of the two coagulants studied (alum and FeCl_3) is effective for remarkable reductions in OM of 36% and 47.4%, respectively. However, EC, by slightly acidifying water, gave better removal efficiencies of the studied parameters. Indeed, the best abatement of OM is about 78% when water is treated with ferric chloride at pH 5.5, lowered with nitric acid. The observed disadvantage here is the residual nitrate, which existed in the raw water at only low level. On the other hand, at the same pH, the reduction of the OM is 64% when alum is used as coagulant. In addition, the data collected have led to the conclusion that the physicochemical quality of the GD water has a high salinity and lowering its pH (EC) does not affect it at all. On the other hand, its pH elevation (AC) considerably reduces its total hardness which is 41% with NaOH. Such a performance advantageously positions this total hardness reduction technology among the possible solutions to the problems associated with total hardness.

Keywords: Conventional Coagulation (CC), Enhanced Coagulation (EC), Alkaline Coagulation, Alum, Lime; Ferric Chloride

1. Introduction

Water is the major element of the mineral and biological world. It is also the privileged vector of life and human activity. However, water in nature is often not directly usable for human consumption or for industry because it is not pure enough. Indeed, during its circulation on the surface of the Earth, water is polluted and carries dissolved and suspended matter: clay particles, waste of vegetation, living organisms (plankton, bacteria, viruses), various salts (nitrates, chlorides,

sulfates, sodium carbonate, calcium carbonate, iron [1], manganese, etc.), organic materials (humic acids, fulvic acids, manufacturing residues, pesticides), and gases [2].

However, it is clear that elimination or inactivation of pathogenic microorganisms by filtration or disinfection has been and continues to be the key requirement for ensuring safe water [3]. The need to remove the compounds responsible for bad tastes and odors, whether of natural or artificial origin,

becomes an important requirement that is additional to the burden of conventional treatment processes. Since the analytical methodology has been significantly improved and the contamination of the aquatic environment is more seriously taken into account, this leads to a growing interest in improved processes to remove these pollutants from water supplies [4].

Thus, coagulation/flocculation, decantation and filtration are irreplaceable processes in conventional treatment for the removal of solid particles and pathogenic microorganisms [5, 6]. Turbidity is considered as the best and rapid indicator of the efficiency of these processes. The regulatory norm regarding drinking water requires from water treatment plants to guarantee a turbidity of less than 5 (or even 0.1) NTU. This turbidity objective can be guaranteed for most water treatment plants at the end of filtration process [7-11].

However, turbidity is not the only parameter to control or optimize after the stage of filtration. In recent decades, special attention has been paid to the elimination of natural organic matter (NOM) as well as pathogenic microorganisms and algae.

The NOM present in raw water is a source of many inconveniences: colors, tastes or odors. It is also involved in the formation of disinfection by-products mainly during chlorination [12-15]. Finally, it interferes with the oxidation of dissolved iron and manganese, thus aggravating the corrosion of pipes and the deterioration of water quality in the distribution network. Eliminating NOM is therefore essential to avoid or minimize health risks and degradation of the distribution network.

Removing NOM by enhanced coagulation (EC) requires the addition of high doses of inorganic coagulants and/or especially an acidic coagulation pH that may even lead to excessive concentrations of the residual metal at the end of the treatment, as well as strong sludge production [16, 17]. Concerning the elimination of the NOM, it can be better carried out, during or after decantation, by the addition of the powdered activated carbon (PAC) as an adsorbent. This step can be expensive because of the high costs of the PAC. The optimization of reagent treatment rates (acid/base, coagulant/flocculant, PAC, etc.) is therefore a technical and economic issue and vital for water treatment [18-20].

The aim of this study is eliminating NOM using EC process, which consists of reducing the pH of water before coagulation before adding different acids and finally performing a comparison between conventional coagulation (CC) and EC. Finally, the main results will be discussed.

2. Materials and Methods

2.1. Presentation of the Ghrib Dam Water Treatment Plant (GDWTP)

The Ghrib Dam (GD) (North of Algeria) is a real hydraulic structure built in 1939. The climate of the study area is generally Mediterranean and the precipitation regime is highly seasonal. The geological formations of the region consist mainly of sandstone and clay marls [21, 22].

The GDWTP is fed from the GD. The development of GDWTP includes firstly a floating raw water intake in the reservoir of the GD which supplies a regulation basin. Secondly, the processing chain consists of two treatment streams that operate in parallel. The two treatment streams comprise a pre-oxidation unit, a coagulation-flocculation step followed by a decantation step, and a sand filtration step, and finally a post-disinfection step.

These two treatment streams are characterized by an identical process of treatment, the only difference being in their capacity. A treatment system that feeds the City of Medea (named *stage III*) whose nominal capacity is 24000 m³; while the treatment system that supplies the City of Berrouaghia (named *stage II*) has a nominal capacity of 12000 m³.

Water is taken from the reservoir by means of four electro-pumps which pump water to a control pond from which it is directly admitted by gravity to the treatment plant itself. The first stage comprises a mixing tank provided with a stirrer, to disperse the reagents, where sodium hypochlorite is added to water for the pre-oxidation process and aluminum sulfate ((Al₂(SO₄)₃.18H₂O), alum) is injected for the coagulation process. This basin is linked directly to another basin provided with more rapid agitation to properly destabilize the colloidal particles. After this step, the flocculation process takes place in three flocculators arranged in series: two are provided with a medium agitation (the first one to disperse the flocculant into water, and the second one to agglomerate the flocs), and the third one with a slow stirring (to do not break the formed flocs). The flocs formed are separated, subsequently, by settling in two circular decanters; the rest of the small flocs being eliminated by fast sand filtration (battery of four filters). Finally, the filtered water is chlorinated after admission to the treated water tank. It is from this reservoir that water is taken up and returned to the places of consumption via an adduction pipe.

Table 1 presents a brief description of the water treatment stages at the GDWTP.

Table 1. Technical presentation of the water treatment stages at the GDWTP.

Stage	Description
<i>Taking of water</i>	The raw water is withdrawn from the reservoir by means of four floating electro-pumps away from the station at 200 m. These groups pump raw water over a control pond.
<i>Control basin (storage)</i>	The raw water is stored in the regulation basin to distribute it into the treatment channels. With a capacity of 1100 m ³ , this basin is also considered as a primary settler which allows eliminating certain fractions of the clays and sand sucked by the pumps, by simple decantation.
<i>Mixing basin</i>	From the regulation basin to the mixing basin, the pre-clarified water arrives gravitationally. In this basin, chemical injection is done: sodium hypochlorite for pre-chlorination and alum for coagulation. The incoming raw water flow is 600 m ³ for Stage III and 450 m ³ for Stage II.
<i>Coagulation process</i>	Coagulation process allows the agglomeration of suspended solids and colloids in water to give rise to a precipitate by the use of

Stage	Description
	a chemical called <i>coagulant</i> which is alum: Number of basins: 2 + 1 Area: $2 \times 4 \text{ m}^2 + 4 \text{ m}^2$ Unit volume: $2 \times 12 \text{ m}^3 + 12 \text{ m}^3$ Fast agitation: 180 rpm Residence time: 2 min Injection point: Mixing basin
<i>Flocculation process</i>	The flocculation process aims to increase the volume and cohesion of the flocs previously formed by coagulation. During a gentle mixing, it consists of adding a flocculation adjuvant that forms "bridges" between the flocs: Number of basins: 6 + 3 Area: $6 \times 4 \text{ m}^2 + 3 \times 4 \text{ m}^2$ Unit volume: $6 \times 12 \text{ m}^3 + 3 \times 12 \text{ m}^3$ Medium agitation: 90 rpm (4 + 2) Slow agitation: 40 rpm (2 + 1) Residence time: 18 min Injection point: First medium agitation basin of flocculation
<i>Decantation process</i>	Decantation is a process of separation of formed flocs, suspended solids, and colloids whose density is greater than that of water. The clarified water near the surface is directed to the filters: Number of decanters: 2 + 2 Type: Circular Diameter: $2 \times 6 \text{ m} + 2 \times 4 \text{ m}$ Unit volume: $2 \times 890 \text{ m}^3 + 2 \times 460 \text{ m}^3$ Area: $2 \times 194.3 \text{ m}^2 + 2 \times 164.7 \text{ m}^2$ Sludge extraction rate: $23.5 \text{ m}^3/\text{h} + 15 \text{ m}^3/\text{h}$
<i>Sand filtration</i>	Filtration is a separation process that uses the passage of a solid-liquid mixture through a porous medium (filter). Filtration retains solid particles and allows the liquid (filtrate) to pass. <i>Sand filters:</i> Number of filters: 8 + 4 Length: 6 m + 6m Width: 3 m + 3m Area: $8 \times 24.5 \text{ m}^2 + 4 \times 24.5 \text{ m}^2$ Maximum filtration speed: 5 to 10 m/h
<i>Disinfection basin</i>	The filtered water is chlorinated with sodium hypochlorite at 48°. To obtain a durable disinfection, it is necessary that the chlorine dose administered is such that it is possible to detect certain residual free chlorine content after a determined contact time. Number: 1 + 1 Capacity: $760 \text{ m}^3 + 360 \text{ m}^3$ Basin area: $165 \text{ m}^2 + 80 \text{ m}^2$ Depth: 3 m + 3 m Residence time: 30 min
<i>Alum dosage</i>	Alum is delivered in bags in the form of aggregates. For the dosage, the preparation of an aqueous solution is done by mixing the grains and water at a rate of $100 \text{ kg}/\text{m}^3$. The injection is carried out directly in the mixing basin. The dose of the injection applied is determined after jar test experiments (the average optimal dose of alum: $30 \text{ g}/\text{m}^3$).
<i>Polyelectrolytes dosage</i>	Polyelectrolytes are delivered in bags in the form of aggregates. For the dosage, the preparation of an aqueous solution is done by mixing grains and water at a rate of $1 \text{ Kg}/\text{m}^3$. The injection takes place directly in the flocculation basin (medium agitation); the dose of the injection applied is determined after jar test experiments (the average optimal dose of polyelectrolytes: $0.2 \text{ g}/\text{m}^3$).
<i>Sodium hypochlorite dosage</i>	Sodium hypochlorite is delivered in liquid form. The injection of sodium hypochlorite into water, for pre-chlorination and disinfection, is done after a chlorine demand (CD) test whose optimal dose is $24 \text{ mL}/\text{m}^3$ and $16 \text{ mL}/\text{m}^3$, respectively.

2.2. Sampling Methods

The natural water source used in this study is GD water. The quality parameters of the raw water over a 7 month period are performed. From these surface waters, a daily production of about $34\,000 \text{ m}^3$ of drinking water is provided to the cities of Medea and Berrouaghia. The raw water samples were collected for our work in limited quantities and periodically from the control basin and transported to the ADE Laboratory on the same day. When samples were received at the laboratory, they were kept cool and dark in order to delay biological activity before analysis.

2.3. Jar Test Experiments Procedure

To determine the optimal coagulation conditions, a series of laboratory-scale tests were used. Experiments on samples of 1 L were carried out using a test apparatus ("Floc Tester/Aqualytic") which makes it possible to obtain, in five beakers of 1 liter of water, rigorously identical and adjustable agitation during the same period thanks to a central control. The standard jar test procedure involves injecting increasing amounts of coagulant and mixing rapidly at 200 rpm for 3 min, slow mixing at 60 rpm for 17 min, and settling for 30 min. To evaluate the performance of the treatment: (1) the formed flocs are observed (time of appearance, size, and appearance); (2) the volumes and masses of the sludge formed are compared; (3) by siphoning, a sample is taken for analysis of

the supernatant in each beaker while avoiding sucking the sludge.

2.4. Used Products

The doses of ferric chloride ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) and aluminum sulfate ($(\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O})$, alum) were varied between 10-50 mg/L prepared from a stock solution of 10 g/L which is prepared periodically. For lowering pH, three acids (0.1 N) were used separately: sulfuric acid (H_2SO_4), hydrochloric acid (HCl), and nitric acid (HNO_3). In order to increase pH, sodium hydroxide (NaOH), at 0.1 N, or lime water ($\text{Ca}(\text{OH})_2$), at 1.6 g/L, were used. All chemicals used in this study are of analytical grade.

2.5. Analytical Methods

A total of 29 variables were subject to physicochemical monitoring. They are determined by colorimetric, volumetric, gravimetric, nephelometric, photometric, and potentiometric analytical methods. The bacteriological examinations carried out concern the enumeration of pollution indicator germs which are: total coliforms, fecal coliforms, fecal streptococci, and sulfite-reducing clostridiums. The method used is that of membrane filtration. The various characteristics of the water samples were determined according to the standard methods of analysis [23, 24]. The details of the analytical methods and the equipment used are presented in Table 2.

Table 2. Analytical methods of the parameters studied.

Parameter	Method
Electrical conductivity (conductivity meter WTW LF 197)	[23]
Turbidity, nephelometric method (HACH turbidimeter)	ISO 7027-1:2016
Temperature (WTW LF 197)	[23]
pH, electrometric determination (pH-meter HANNA)	[23]
Calcium (Ca^{2+}), titrimetric method with ethylenediaminetetraacetic acid (EDTA)	ISO 6058:1984
Magnesium (Mg^{2+}), titrimetric method with EDTA	ISO 6058:1984
Chlorides (Cl^-) (Mohr method)	ISO 9297:1989
Total hardness, titrimetric method with EDTA	[23]
Oxidability with potassium permanganate (KMnO_4) (<i>permanganate index</i>)	ISO 8467:1993
Sodium (Na^+) and potassium (K^+), flame photometry method (CORNING)	ISO 9964-3:1993
Nitrates (NO_3^-), spectrophotometric method (UV-Vis SPECOL spectrophotometer)	ISO 7890-3:1988
Nitrites (NO_2^-), spectrophotometric method (UV-Vis SPECOL spectrophotometer)	[23]
Ammonia nitrogen (NH_4^+) (<i>ammonium</i>), spectrophotometric method (UV-Vis SPECOL spectrophotometer)	ISO 7150-1:1984
Phosphates (PO_4^{3-}), spectrophotometric method (UV-Vis SPECOL spectrophotometer)	ISO 6878:2004
Iron (Fe), spectrophotometric method (UV-Vis SPECOL spectrophotometer)	ISO 6332:1988
Sulfates (SO_4^{2-}), spectrophotometric method (UV-Vis SPECOL spectrophotometer)	[23]
Chemical oxygen demand (COD)	ISO 6060/1989-10-15
Biological oxygen demand (BOD_5) (AQUA Lytic BOD meter)	[23]
Chlorophyll <i>a</i> , spectrophotometric method (UV-Vis SPECOL spectrophotometer)	[23]
Dry residue, gravimetric method	[23]
Total coliforms	[23]
Fecal coliforms	[23]
Fecal streptococci	ISO 7899-1:1998
Clostridium sulfite-reducer	ISO 6222:1999
Salmonella typhi	[23]
Cholera vibrio	[23]

3. Results and Discussion

This study was performed from February to August 2012. Physicochemical and bacteriological analyses were performed to evaluate the contents of GD water.

3.1. Physicochemical and Bacteriological Parameters of GD Water

The results of physicochemical analyzes of GD water are reported in Table 3.

Table 3. Physicochemical analyzes of GD water.

Parameter	Month (2012)							Parametric value [25]
	February	Mars	April	May	June	July	August	
Electrical conductivity ($\mu\text{S}/\text{cm}$, 25°C)	3250	3250	3080	3200	3240	3250	3320	2500**
Dry residue (mg/L)	2157	2160	2004	2175	2204	2210	2250	
Total hardness (mg/L)	955	745	625	630	655	769	nd*	
Mg^{2+} (mg/L)	216	229	179	150	151	157	184	50****
Ca^{2+} (mg/L)	210	198	158	148	146	152	148	
Cl^- (mg/L)	428	337	415	530	532	530	453	250***
SO_4^{2-} (mg/L)	769	998	352	394	393	392	523	
Na^+ (mg/L)	265	280	320	385	387	386	292	200****

Parameter	Month (2012)							Parametric value [25]
	February	Mars	April	May	June	July	August	
K ⁺ (mg/L)	8	6	8	8	8	8	8	
pH	8	7.4	8	7.7	8	8	8.1	6.5-8.5****
Total alkalinity (mg/L as CaCO ₃)	110	110	123	110	102	105	100	
Turbidity (NTU)	6.53	6.53	7.55	6.66	4.73	7.31	8.47	
KMnO ₄ oxidability (mg/L)	7.2	6.5	6.8	7.3	8	9.7	9.8	
COD (mg/L)	37	13	38	19.6	19.8	19	19	
BOD ₅ (mg/L)	5	5	2	4	6	8.5	8.5	
COD/BOD ₅	7.4	2.6	19	4.9	3.3	2.2	2.2	
NO ₃ ⁻ (mg/L)	nd*	4	3.2	5.6	3.8	4.3	4.2	50***
GD volume (Mm ³)	95	103	136	127	125	118	109	
GD water temperature (°C)	8.1	11.7	14.7	20.2	23.8	26.5	26.5	
GD air temperature (°C)	15	22	17	32	30	41	26	
Chlorophyll <i>a</i> (µg/L)	0.9	0.8	1	1.6	1.2	2	2.9	
Total coliforms (/100 mL)	3850	2778	4100	3100	4962	5040	5378	
Fecal coliforms (/100 mL)	7	3	3	10	7	15	10	
Fecal streptococci (/100 mL)	1	0	0	0	22	50	35	
Clostridium sulfito-reducer (/20 mL)	1	0	0	6	15	1	1	

*nd: Not determined.

**2500 µS/cm at 20°C (European Union).

***Cl⁻ (European Union).

****Canada.

By analyzing the values of the electrical conductivity which is in direct relation with the dry residue, GD water is mineralized but does not present a large variation during the year. This high mineralization is due to elevated levels of dissolved salts including sodium and potassium chlorides, sulfates, and calcium and magnesium hardness. These are at above-standard rates with more or less stable concentrations during the year and are directly related to the geological nature of the GD watershed. An inflection of the conductivity is observed during the months of March, April and May. This is explained by the dilution phenomenon following the rainfall and snowfall (February) on the watershed. The high hardness is attributed to the presence of the "blue marl" rock (a sedimentary rock containing CaCO₃ limestone and clay) which constitutes the bottom of the GD. Also, from a concentration of 100 mg/L, magnesium gives the water a bitter taste [23]. The water analysis shows high concentrations of chloride ions (Cl⁻) compared to the standards in force (<250 mg/L). This content could be explained by the nature of the land in the watershed located on saline soil and by wastewater discharges. GD water has high sulfate concentrations. The geology of the dam is marked by the absence of gypseous rocks and pyrites suggesting that the origin of these very high levels in sulfate is probably due to the release of water from the Bougezoul Dam (near GD). The sodium content is important. It depends on the terrain crossed mainly sedimentary rock that gives the water a salty taste. The potassium content is low and poses no problem as for its consumption. It is found that the GD water is slightly alkaline. The total alkalinity has more or less stable values. The alkalinity of water corresponds to the presence of hydroxide ions, carbonates and bicarbonates; and to a lesser extent to phosphate and silicate ions.

It is the particles in suspension which are at the origin of the turbidity [26]. Indeed, the erosion of the rocks, the training of the mineral and organic matter (OM) of the soil, the discharge

of the wastewater can inevitably lead to the increase of the turbidity. According to the obtained results, the turbidity is rather weak since the water sampling is done on the surface.

The GD water contains amounts of OM (measured in terms of KMnO₄ oxidability) (between 6.5 and 9.8 mg O₂/L). According to Rodier [23], water is of poor quality if its KMnO₄ oxidability is greater than 4 mg/L. The OM could come from pollution either of endogenous origin, generated during the biological processes within the medium, mainly, the algal excretion, cell lysis, or of exogenous origin brought by the urban discharges, the agricultural practices or soil leaching. These OM amounts can complicate the treatment of water with the formation of disinfection by-products, since there is a pre-oxidation at the beginning (treatment with chlorine) [27].

During the study period, the results of the COD show that the maximum load (38 mg O₂/L) does not largely exceed the guideline value which is 30 mg/L maximum [23]. The same remark is about the results obtained for the BOD₅.

Nitrates are at levels of the order of 5.6 mg/L. These concentrations are much lower than the maximum acceptable concentration according to the European Union Standards which is of the order of 50 mg/L.

Exceptionally in this year 2012, in GD raw water, the ammonium, nitrite and phosphate levels are almost zero. This is explained by the climatic conditions experienced by the region in winter and early spring (the overflow of the Grib Dam Lake due to heavy rainfall and significant melting of snow). Indeed, on April 19, 2012, the water level exceeded the maximum of 136,476 million m³ and ended up overflowing via the large spillway.

The temperature of the surface waters is largely conditioned by the temperature of air and the solar energy. The water temperature of GD varies between 8.1°C in February and 26.5°C in August.

The chlorophyll *a* content is clearly influenced by several

factors such as the composition and physiological state of the algae, the cell density, the light, the temperature of water, and the time of day at which sample is taken. Chlorophyll *a* levels were low during the study period, ranging from 0.81 to 2.9 µg/L. This is due to the climatic conditions mentioned above.

As for total coliforms, their number is significant but without exceeding the usual content of raw water for treatment for the production of drinking water. As for fecal coliforms, the analyzes carried out mention a low concentration, the maximum of which does not exceed 15/100 mL in the month of July. For fecal streptococci, no detections were recorded during the cold period. Then, a sudden onset of concentrations of 22, 50 and 35 in 100 mL of water in the months of June, July, and August, respectively. This is explained by the rise in temperature in this season. Clostridial sulphite-reducing

spores are not as numerous; we have two peaks of 6 and 15 spores/20 mL in May and June, respectively (Table 2).

3.2. CC with Ferric Chloride and Alum

The removal of organic precursors by the coagulation process is influenced by several factors such as coagulation conditions and NOM characteristics [28, 29]. The choice of coagulant is a key factor in the performance of the coagulation process [30]. For this reason, the efficiency of ferric chloride was compared to that of alum. The comparative study on these two coagulants was carried out without adjusting pH of the raw water. The following parameters were evaluated: turbidity (Figure 1), OM (Figure 2), CD (Figure 3), and COD (Figure 4).

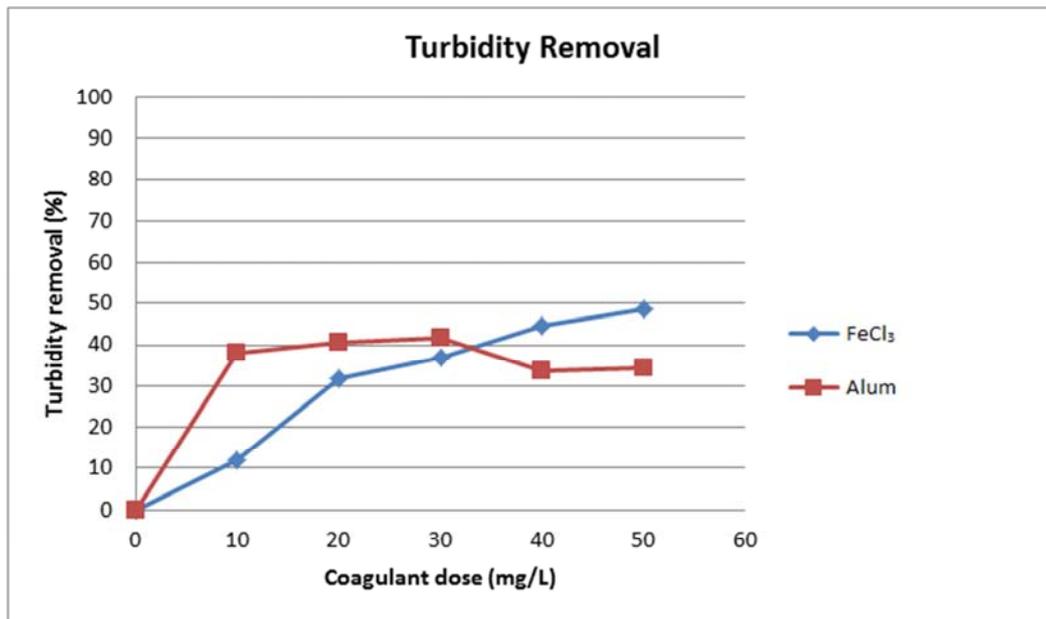


Figure 1. Reduction of the water turbidity of GD as a function of the dose of the coagulant (alum and ferric chloride).

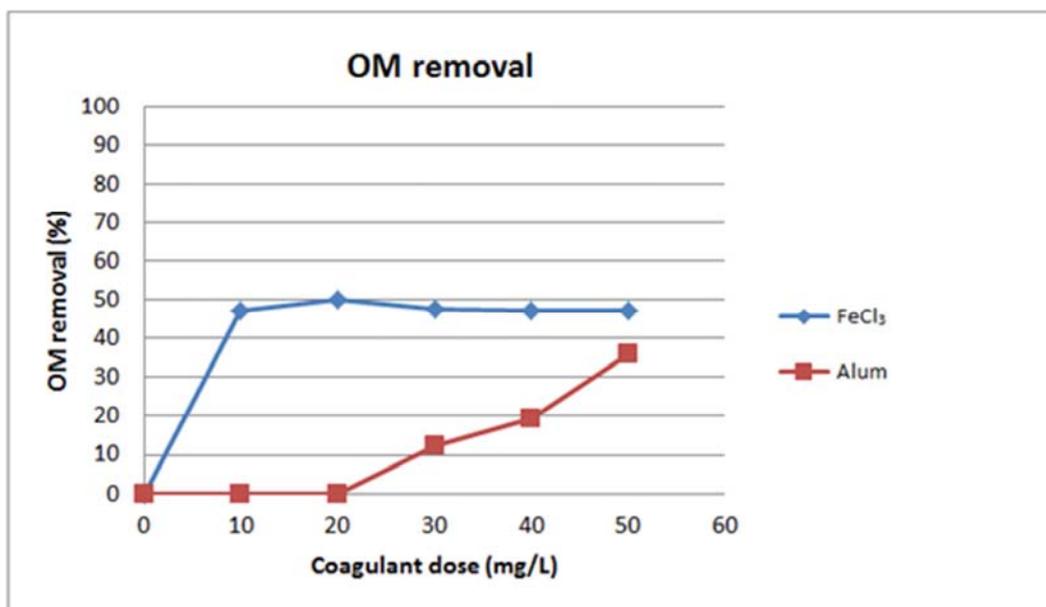


Figure 2. Reduction of the OM of GD water as a function of the dose of the coagulant (alum and ferric chloride).

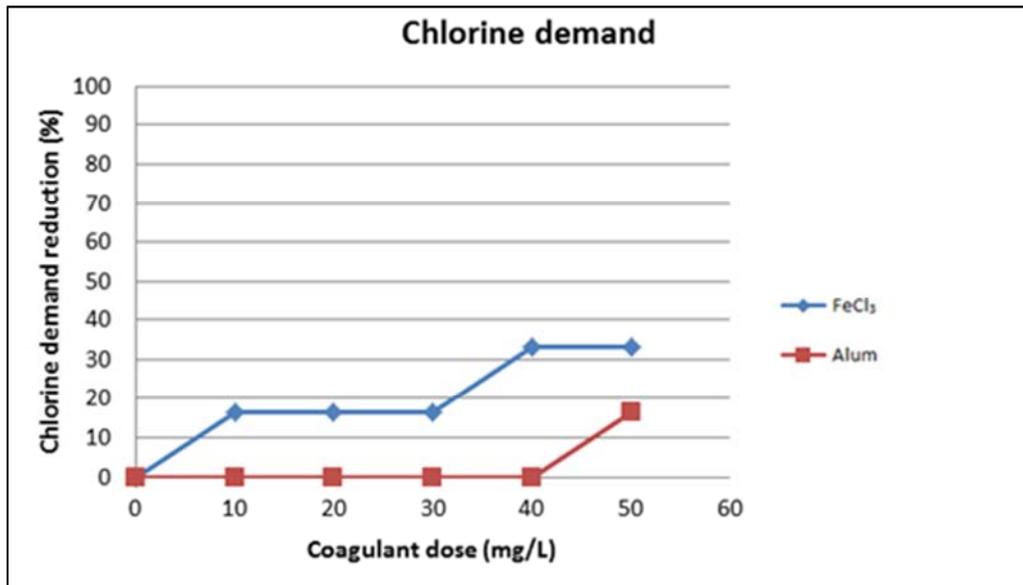


Figure 3. Reduction of CD of GD water as a function of the dose of the coagulant (alum and ferric chloride).

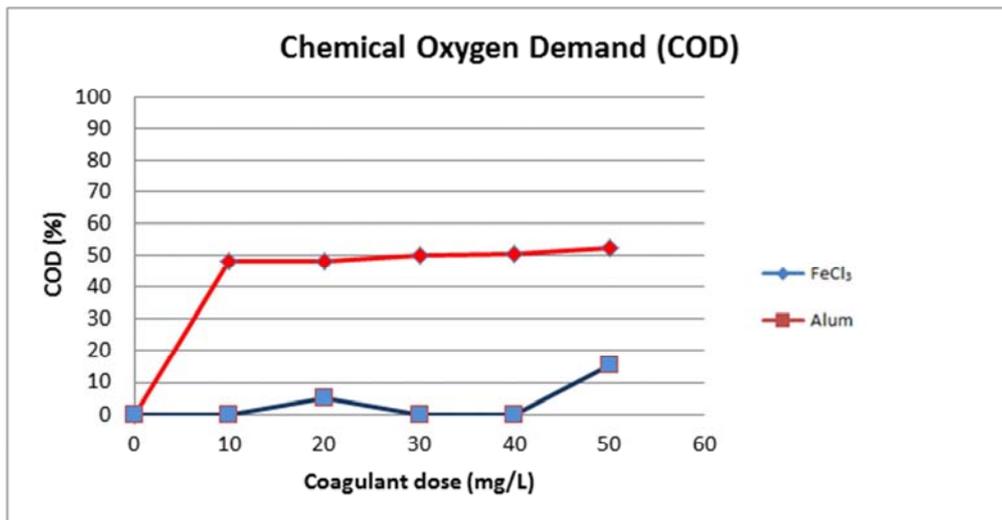


Figure 4. Reduction of the COD of GD water as a function of the dose of the coagulant (alum and ferric chloride).

Table 4. Optimum yield following the two coagulants used for the CC of GD water.

Parameter	Efficiency (%) of the coagulant at 50 mg/L	
	Alum	Ferric chloride
OM (KMnO ₄ oxidability)	36	47
Turbidity	34	36
COD	15	52
CD	17	33
BOD ₅	100	100
Total coliforms	17	90
Fecal coliforms	80	100
Fecal streptococci	100	100
Clostridium sulfito-reducer	100	100
Chlorophyll <i>a</i>	68	72

Several studies have shown a better performance for ferric chloride than for alum.

As shown in Figures. 1-4, the coagulation data indicate that as each dosage of coagulants increased further, the amount of

removal was also increased gradually [31]. An average coagulant dosage was found in the vicinity of 30 mg/L (this is the dose used at the GDWTP). Although this dose gave satisfactory results, a coagulant dose of 50 mg/L was chosen for the EC studies since it gave better results. The 50 mg/L dose of the two coagulants allows a better reduction of everything related to coagulation: turbidity, OM, COD, CD, BOD₅, chlorophyll *a*, and microbial flora. The reduction rates of these parameters are listed in Table 4.

3.3. EC with Ferric Chloride and Alum

Determining EC conditions requires the evaluation of both optimal pH and coagulant dosage. To determine the optimal pH for a selected coagulant dose (alum and ferric chloride), the jar tests were performed using a constant coagulant dose and varying the pH of the coagulation using sulfuric acid, hydrochloric acid, and nitric acid.

3.3.1. Alum Experiments

For alum, the optimal pH of coagulation was identified as the

pH at which there was the highest removal of turbidity (Figure 5), OM (Figure 6), CD (Figure 7), and COD (Figure 8).

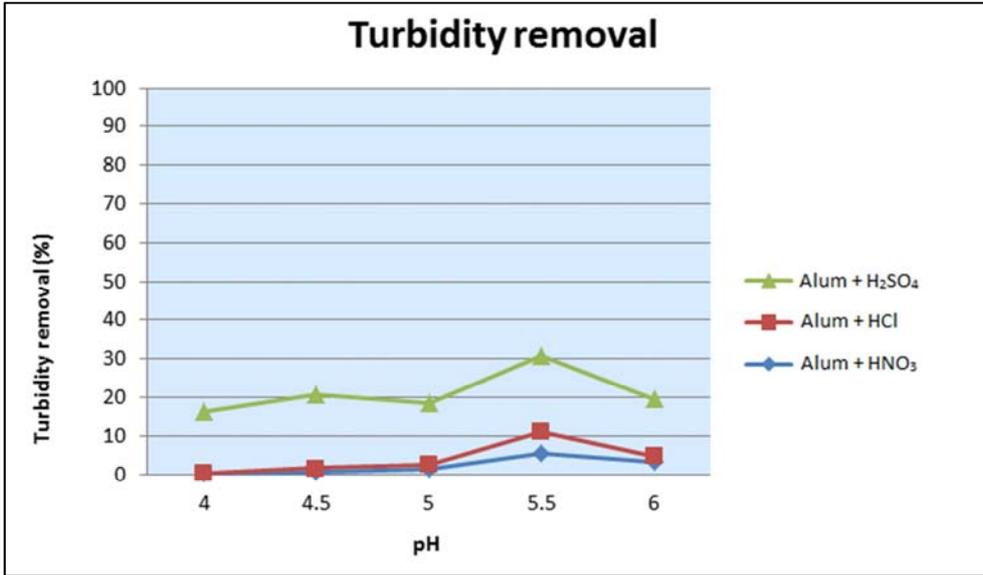


Figure 5. Reduction of turbidity as a function of pH (HCl, HNO₃ and H₂SO₄) with a fixed dose of alum.

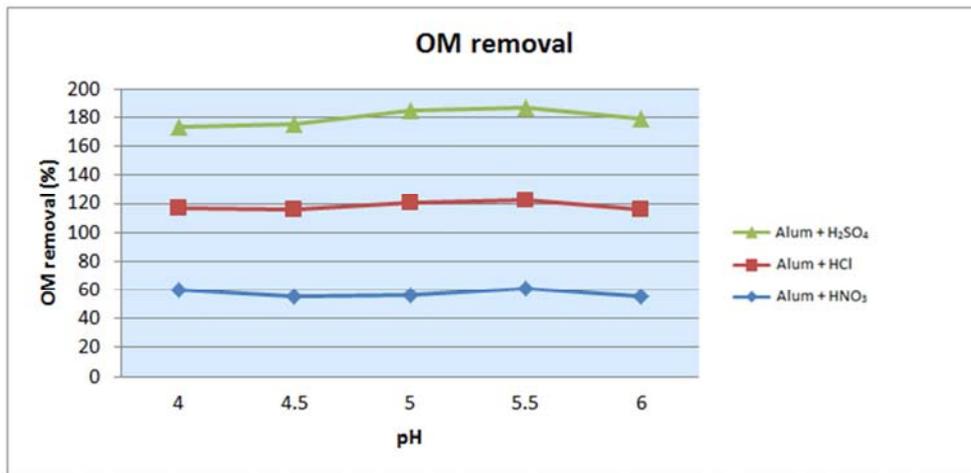


Figure 6. Reduction of OM as a function of pH (HCl, HNO₃ and H₂SO₄) with a fixed dose of alum.

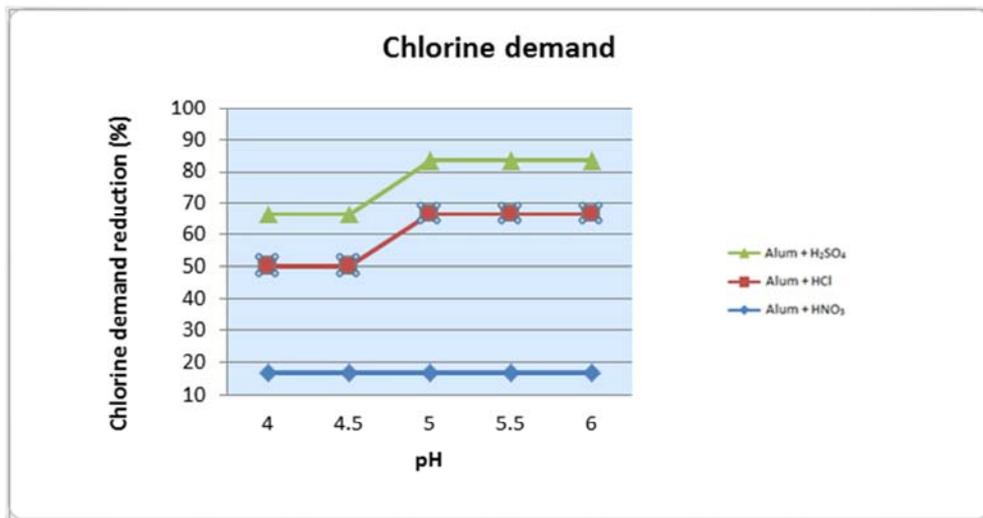


Figure 7. Reduction of CD as a function of pH (HCl, HNO₃ and H₂SO₄) with a fixed dose of alum.

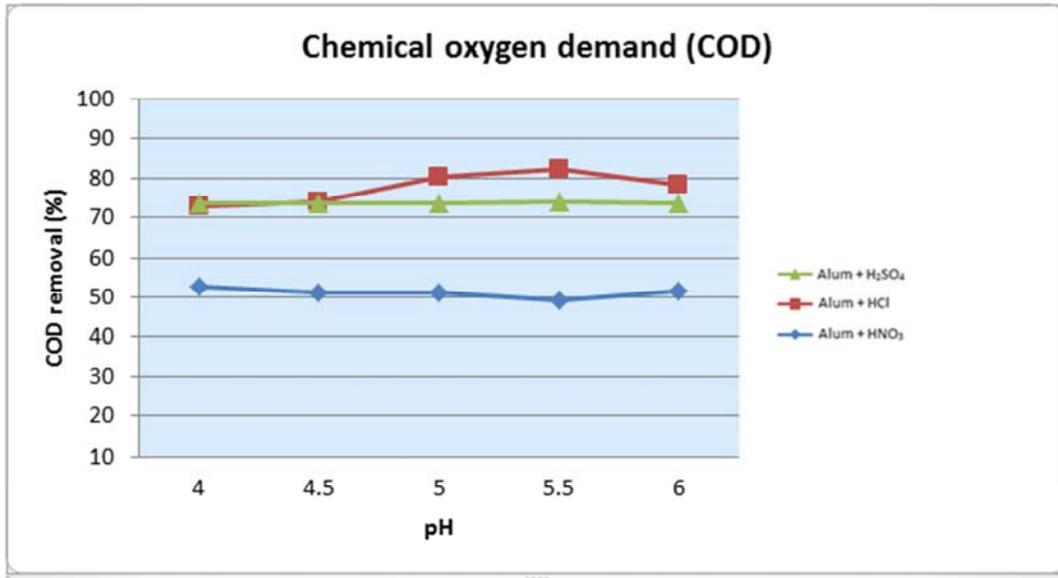


Figure 8. Reduction of COD as a function of pH (HCl, HNO₃ and H₂SO₄) with a fixed dose of alum.

Table 5. EC with alum using sulfuric acid, hydrochloric acid, and nitric acid.

EC with alum performance (%)			
Parameter	HNO ₃	H ₂ SO ₄	HCl
Turbidity	5.5	19.7	5.6
OM	63.9	60.8	61.8
CD	16.7	16.7	50
COD	74.2	49	82.6

In preliminary observation, we noticed that the flocs appeared only late, they are very fine and difficult to decant after 30 min. As shown in Figures. 5-8, the results obtained proved that the low pH coagulation process is effective towards the reduction of the parameters examined. The optimum of the elimination corresponds to a pH of 5.5 with the reduction rates mentioned in Table 5.

3.3.2. Ferric Chloride Experiments

For alum, the optimal pH of coagulation was identified as the pH at which there was the highest removal of turbidity (Figure 9), OM (Figure 10), CD (Figure 11), and COD (Figure 12).

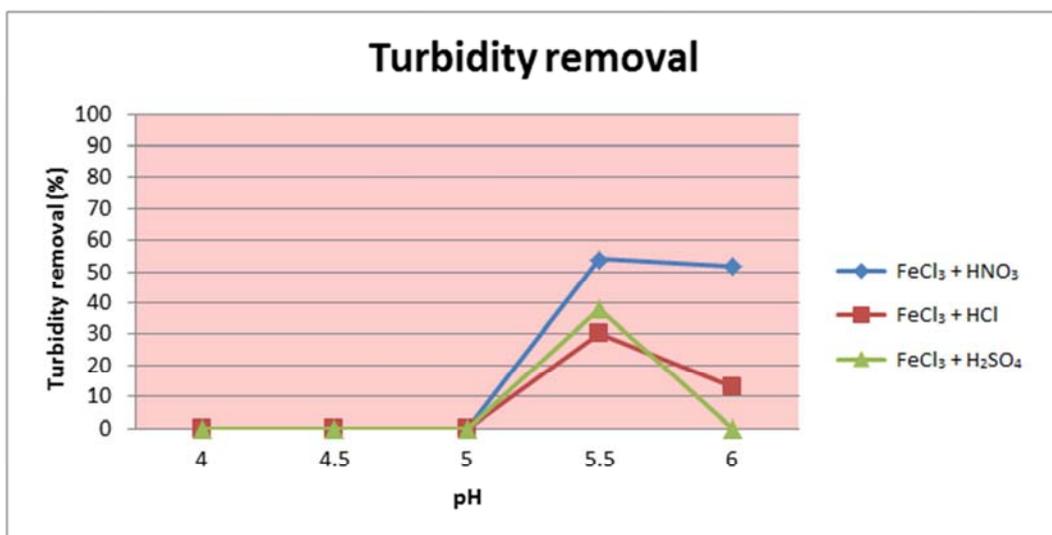


Figure 9. Reduction of turbidity as a function of pH (HCl, HNO₃ and H₂SO₄) with a fixed dose of FeCl₃.

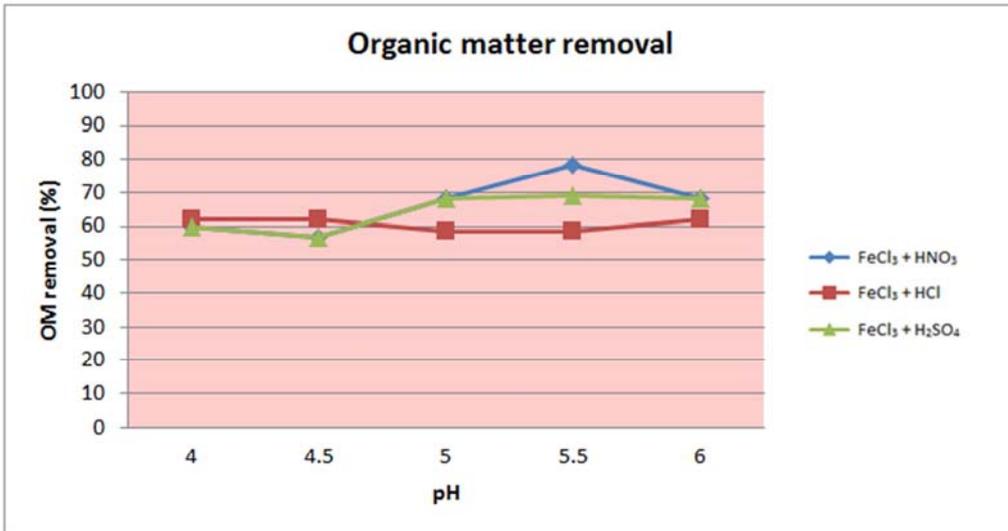


Figure 10. Reduction of OM as a function of pH (HCl, HNO₃ and H₂SO₄) with a fixed dose of FeCl₃.

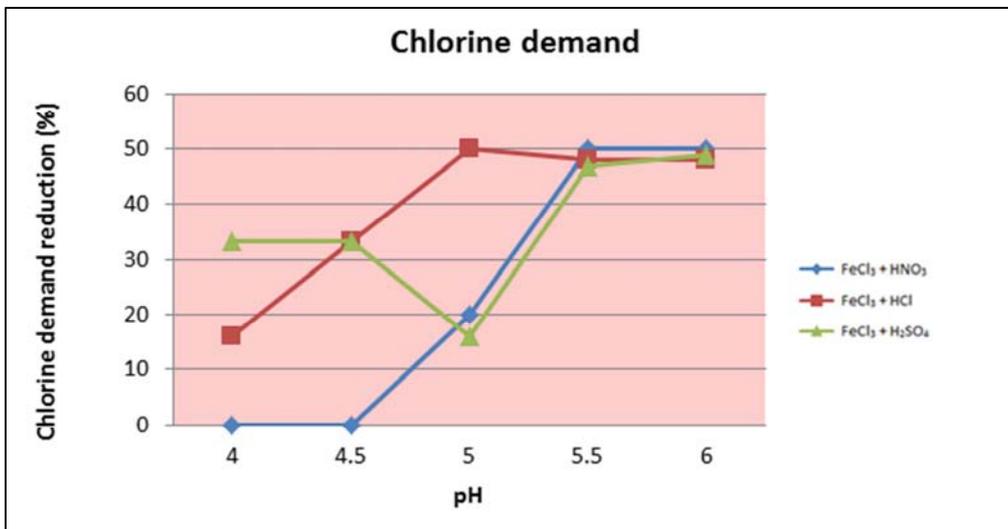


Figure 11. Reduction of CD as a function of pH (HCl, HNO₃ and H₂SO₄) with a fixed dose of FeCl₃.

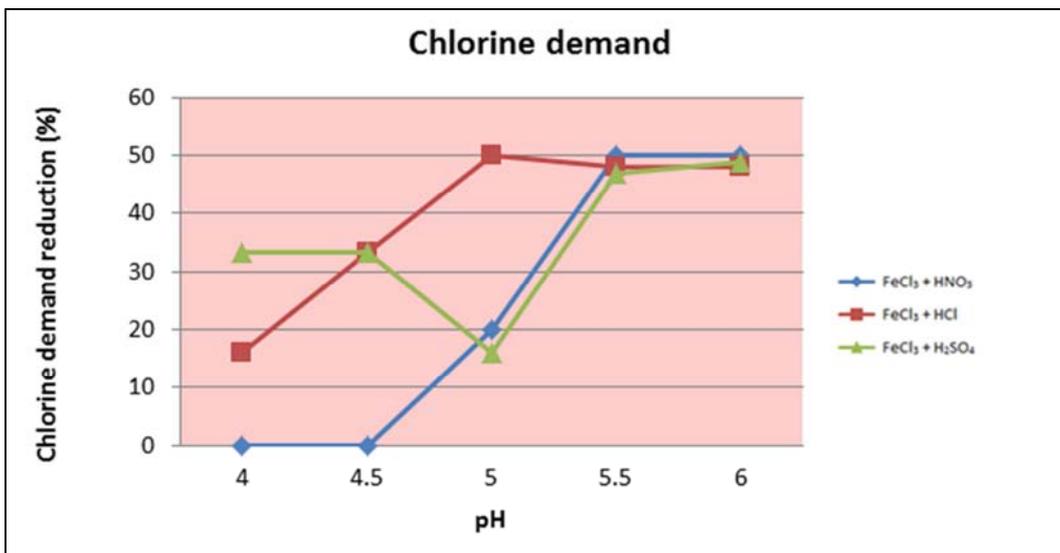


Figure 12. Reduction of COD as a function of pH (HCl, HNO₃ and H₂SO₄) with a fixed dose of FeCl₃.

The different water samples from the GD coagulated at fixed doses of ferric chloride (50 mg/L) and at increasing pH show the appearance of large dense flocs (rapid settling) between pH 5.5 and 6. As shown in Figures. 9-12, the optimum of the elimination of the various parameters corresponds to a pH of 5.5 with a reduction rate listed in Table 6.

Table 6. EC with ferric chloride using sulfuric acid, hydrochloric acid, and nitric acid.

EC with ferric chloride performance (%)			
Parameter	HNO ₃	H ₂ SO ₄	HCl
Turbidity	54	38	30
OM	78.3	69	58.7
CD	50	50	50
COD	100	91	87

As seen in Table 6, the results obtained demonstrate clearly

that the application of FeCl₃ with the addition of HNO₃ for pH adjustment to 5.5 is the best suited for the reduction of turbidity, OM, COD, BOD₅, and microorganisms. In terms of efficiency, H₂SO₄ and HCl arrive at the second position.

3.4. Alkaline Coagulation (AC) with Ferric Chloride and Alum

Since the GD water is well-known for its high salinity and hardness, we thought to examine the effect of adding a base to the water in order to increase its pH before the injection of the coagulant to illustrate the effect of hydroxyl ions (OH⁻) on the precipitation of Mg²⁺ and Ca²⁺ ions. In other words, the experimental procedure adopted in this part of this study is the opposite of what was done with the EC based on the acidification of water before coagulation. The results obtained are illustrated and discussed in the following.

For alum, the obtained results are shown in Figures. 13-16.

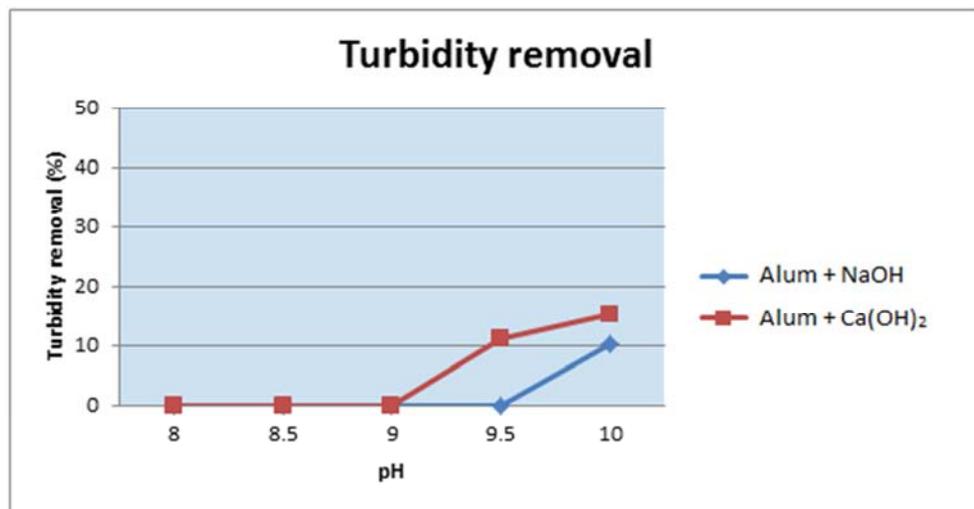


Figure 13. Removal of turbidity as a function of basic pH (Ca(OH)₂ and NaOH) with a fixed dose of alum.

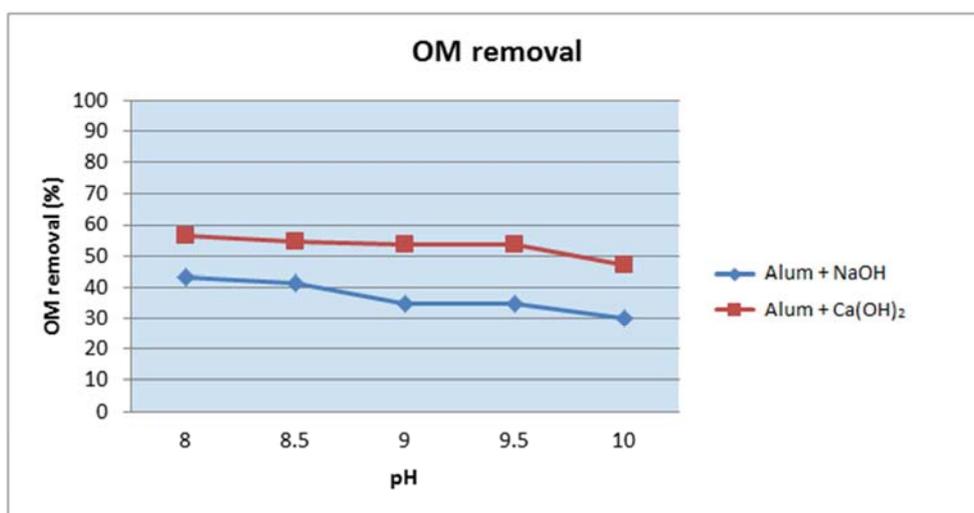


Figure 14. Removal of OM as a function of basic pH (Ca(OH)₂ and NaOH) with a fixed dose of alum.

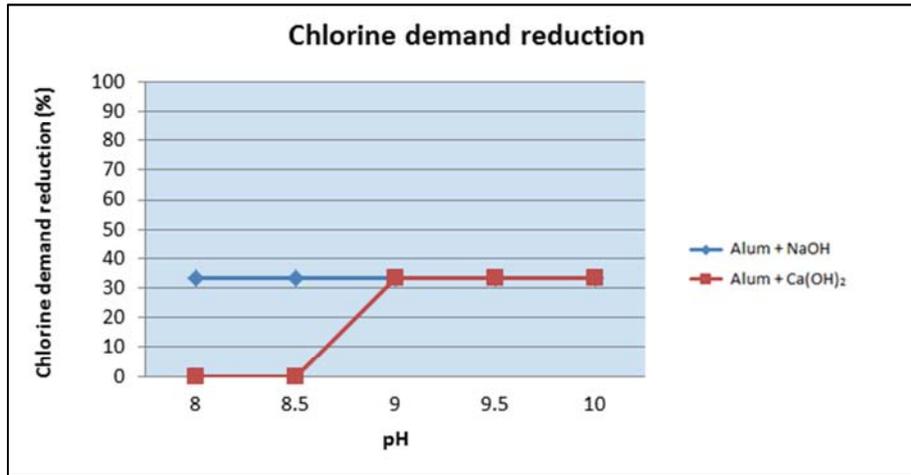


Figure 15. Reduction of CD as a function of basic pH (Ca(OH)_2 and NaOH) with a fixed dose of alum.

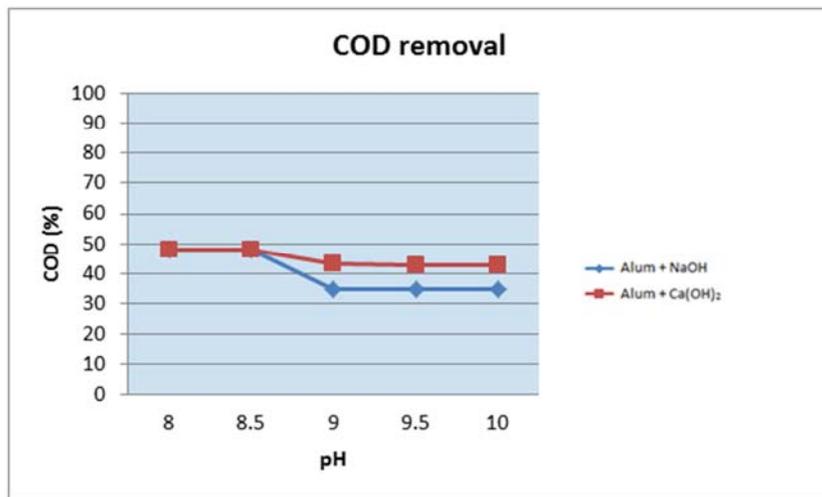


Figure 16. Removal of COD as a function of basic pH (Ca(OH)_2 and NaOH) with a fixed dose of alum.

Table 7. Alkaline coagulation (AC) with alum using lime and NaOH.

AC with alum performance (%)		
Parameter	Lime (Ca(OH)_2)	NaOH
Turbidity	15.2	10.2
OM	56.7	43.3
CD	33.3	33.3
COD	47.9	47.9

in the presence of lime and NaOH at pH 8, but at much lower levels than with the acids tested previously. The alum performances may be listed in Table 7.

An increase in the volume of sludge at the end of settling is noticed.

For ferric chloride, the obtained results are shown in Figures. 17-20.

All the tests show that alum has a good coagulation capacity

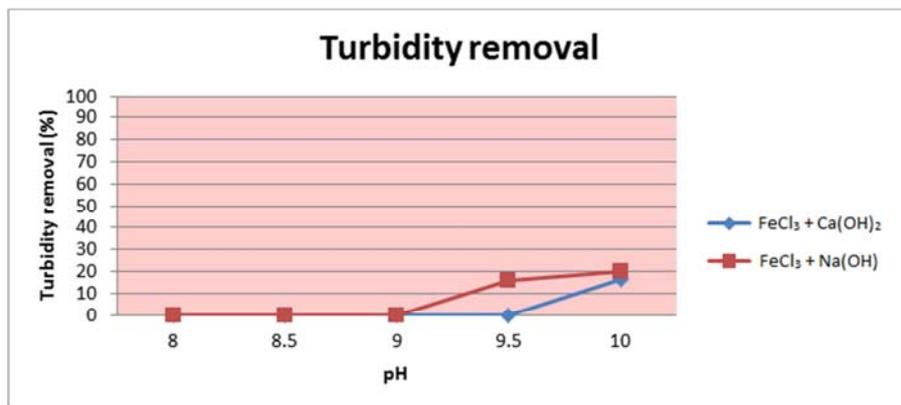


Figure 17. Removal of turbidity as a function of basic pH (Ca(OH)_2 and NaOH) with a fixed dose of ferric chloride.

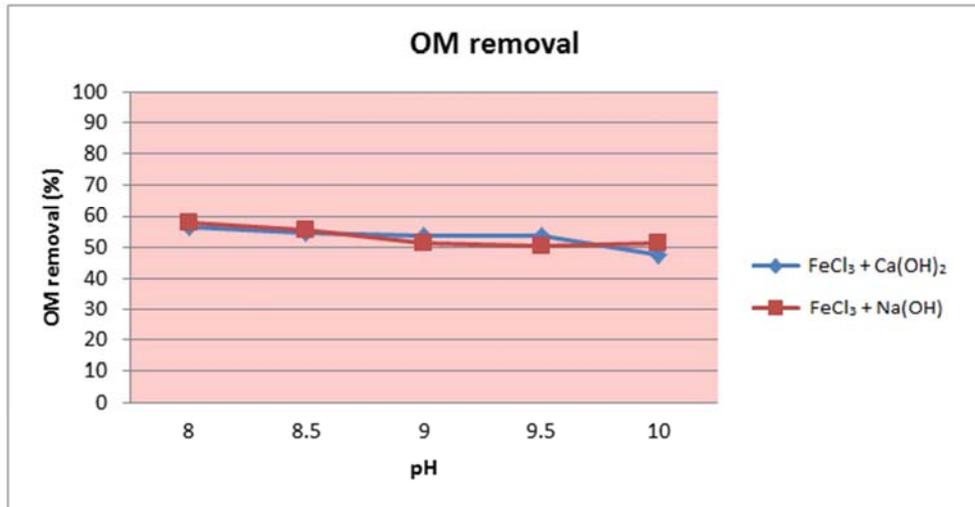


Figure 18. Removal of OM as a function of basic pH (Ca(OH)_2 and NaOH) with a fixed dose of ferric chloride.

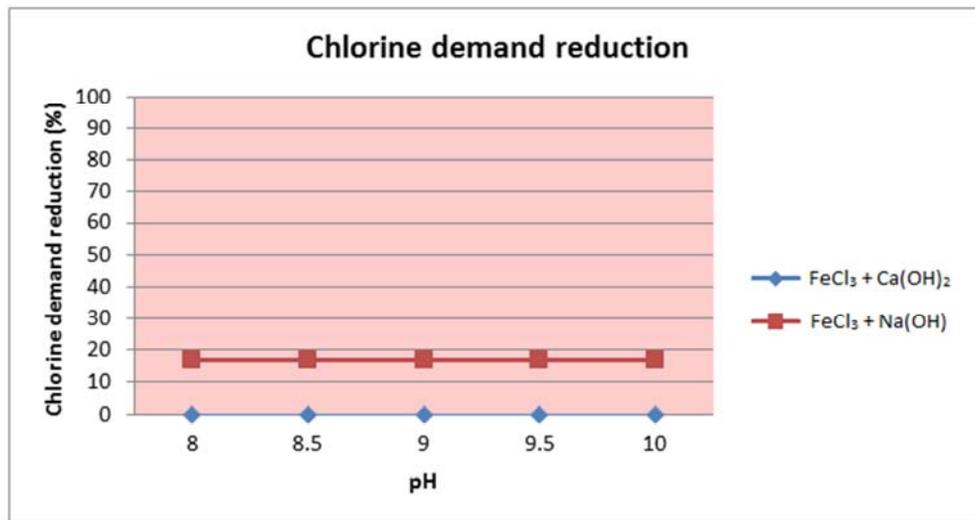


Figure 19. Reduction of CD as a function of basic pH (Ca(OH)_2 and NaOH) with a fixed dose of ferric chloride.

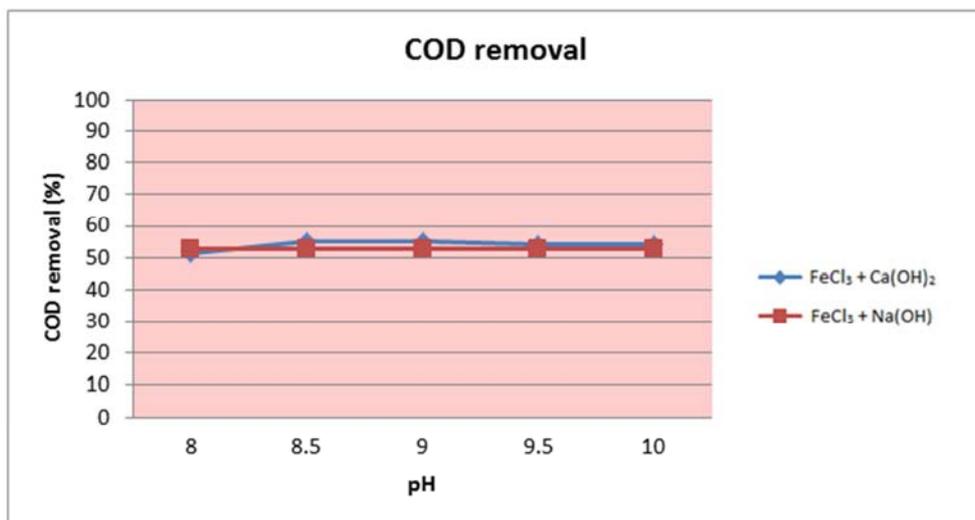


Figure 20. Removal of COD as a function of basic pH (Ca(OH)_2 and NaOH) with a fixed dose of ferric chloride.

As seen in Figures 17-20, the results with ferric chloride are similar to those of alum. The most appreciable removal is at

pH 8 with either lime or soda. The best reduction rates are listed in Table 8.

Table 8. AC with ferric chloride using lime and NaOH.

AC with ferric chloride performance (%)		
Parameter	Lime (Ca(OH) ₂)	NaOH
Turbidity	16.2	20
OM	56.7	57.7
CD	0	16.6
COD	52.6	56.7

3.5. General Discussion

The results obtained show that, contrary to the use of coagulants alone (i.e., CC), lowering pH (i.e., EC [16]) makes

Table 9. Softening efficiency of the two bases, Ca(OH)₂ and NaOH.

Coagulant	NaOH			Ca(OH) ₂		
	Total hardness removal (%)	Ca removal (%)	Mg removal (%)	Total hardness removal (%)	Ca removal (%)	Mg removal (%)
FeCl ₃	41.3	46	41	0.1	0.1	0.1
Alum	40	46	39.8	13.2	0.01	0.1

The lime (Ca(OH)₂) did not give good results; maybe it would be necessary to go to higher pH and to eliminate the excess of lime by addition of CO₂.

4. Conclusions

The main points drawn from this work are listed as below:

This study demonstrated the effectiveness of GD water treatment by the EC process compared to CC.

The results obtained confirm the bibliographic data concerning the elimination of organic compounds for pH levels globally between 5 and 7 depending on the nature of the coagulant. Indeed, it has been demonstrated that each of the two coagulants studied (alum and FeCl₃) is effective for remarkable reductions in OM of 36% and 47.4%, respectively. Turbidity, pathogenic microorganisms, COD, BOD₅, chlorophyll *a*, and CD are eliminated at significant rates.

However, EC, by slightly acidifying water, gave better removal efficiencies of the studied parameters. Indeed, the best abatement of OM is about 78% when water is treated with ferric chloride at pH 5.5, lowered with nitric acid. The observed disadvantage here is the residual nitrate, which existed in the raw water at only low level. On the other hand, at the same pH, the reduction of the OM is 64% when alum is used as coagulant.

In addition, the data collected have led to the conclusion that the physicochemical quality of the GD water has a high salinity and lowering its pH (EC) does not affect it at all. On the other hand, its pH elevation (AC) considerably reduces its total hardness which is 41% with NaOH. Such a performance advantageously positions this total hardness reduction technology among the possible solutions to the problems associated with total hardness. This observation suggests that it could attract the attention of stakeholders in the water treatment. This is all the more the case when one considers that, at first glance, the additional expenses associated with the

it possible to have larger flocs settling more rapidly (the phenomenon of piston settling is more pronounced) especially with ferric chloride. This is because the floc formed by the iron-based coagulants is heavier than the alumina floc. In addition, it appears that ferric chloride is more effective in eliminating turbidity and OM than alum.

For the AC, Ca(OH)₂ and (NaOH) used to alkalize the medium tend to form agglomerates of dense crystals decanting at high speed [23]. In addition, a decrease in total hardness and total alkalinity is observed; this can result in maximum precipitation of metal hydroxide (Al(OH)_{3(s)} or Fe(OH)_{3(s)}) during flocculation and decantation as well as an increase in sludge production [32]. Table 9 presents the softening efficiency of the two bases, Ca(OH)₂ and NaOH.

implementation and operation of the process do not seem to be an insurmountable burden, especially in view of the fact that the OM removal of the treated water is paramount.

Acknowledgements

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List of Abbreviations

AC	Alkaline coagulation
BOD ₅	Biological oxygen demand
CC	Conventional coagulation
CD	Chlorine demand
COD	Chemical oxygen demand
EC	Enhanced coagulation
GD	Ghrib Dam
GDWTP	Ghrib Dam Water Treatment Plant
NOM	Natural organic matter
OM	Organic matter

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