Design of a Chemically Enhanced Primary Treatment Plant for the City of Alfenas, Minas, Gerais, Brazil

by

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Abstract

This thesis proposes using Chemically Enhanced Primary Treatment as a first solution to the environmental, human health and water quality problems that have arisen in the Furnas Lake region of the state of Minas Gerais, Brazil. The lake has experienced a dramatic loss of volume and deterioration of its water quality in the past four years, a condition exacerbated by the direct discharge of wastewater from the 140 cities surrounding it. A plant will be proposed to serve a portion of the population of the city of Alfenas, located at the southwestern edge of the Furnas Lake, as a modular example to be replicated throughout the region. Field research results of bench scale testing of the wastewater and laboratory analysis results will be presented and analyzed to support design parameters. Two proposed treatments will be compared in terms of efficiency in treatment, cost effectiveness and other considerations. A preliminary plant design will be presented, along with proposed layout, location and equipment specification guidelines.

Thesis Supervisor: Dr. E. Eric Adams
Title: Senior Research Engineer

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1. Introduction

1.1 Water and Sanitation in Developing Countries

Industrialized countries have reached optimal levels of water and sanitation services due to the availability of the necessary technological and monetary resources. However, this situation is seldom found in developing countries, particularly in rural areas.

The main challenge of bringing proper water and sanitation services to the developing world is that of doing so in a cost-effective manner. Experiences from the past, especially during the 1980's, the so-called "International Water and Sanitation Decade," have shown that simply providing the technology is not enough. This technology needs to be sustainable using resources that are locally available. Furthermore, water and sanitation projects often focus on large urban areas, as it is easier to provide service in a more densely populated setting, hindering the possibilities of low-income rural regions to have access to these services.

Latin America is the region with the most abundant water resources in the world, practically doubling the amount of freshwater available per capita compared to the next region in the ranking, Europe and Central Africa (World Bank Atlas, 1998). In spite of this apparent abundance, the Amazon has experienced a gradual but relentless loss of water, triggered by systematic deforestation and other abuses of resources. Currently, the area is experiencing a generalized drought, an example of which is the Furnas region in the state of Minas Gerais, which is the focus of this thesis. Figure 1-1 shows a map of Brazil where the Furnas region, in the southwestern quadrant, has been highlighted.

Figure 1-1: Map of Brazil, FURNAS region highlighted

(Source: http://geocities.yahoo.com.br/brasil_tur/mapa_bra.htm)

1.2 Current Status of the Furnas Reservoir Region

In 1963, the first FURNAS hydroelectric power plant (shown in Figure 1-2) began operation. FURNAS is one of the major energy generation companies in Brazil and its main objective building this plant was to mitigate the energy crisis emerging in Brazil at the time. Capturing the waters of the Grande River, the Furnas Lake was formed, with a surface of 1,440 km^2, and a dendritic geometry due to the predominantly mountainous topography of the area. Overcoming the initial difficulties that the formation of the lake presented to the region, for instance disabling a train line that was used for commerce and passengers, it grew into an important resource for recreation and tourism. In addition, many neighboring cities depend on it for their water supply and to dispose of their wastewater.

Figure 1-2: FURNAS hydroelectric power plant, built in 1963
(Source: http://www.furnas.com.br)

At present, this FURNAS power plant provides 163 kWh per month for 23,000 households. The lake provides 99% of the fresh water supply for the region, and collects 98% of the sewage produced (FURNAS website, http://www.furnas.com.br).

Four years ago, a combination of severe drought and overworking of the power plant, due to rapid economic growth in the region, led to a major loss of water in the lake. Today, water is at a volume equal to 11% of its original volume (Fateen, 2002).

This situation is aggravated by the fact that the surrounding municipalities discharge their wastewater directly into the lake or, now that it has receded, to the ground immediately around it. Untreated wastewater released into the lake elevates the risks to human health, specifically that of waterborne disease outbreaks. The lower water volume exacerbates these risks by increasing pollutant concentrations in the reservoir.

In addition, a major environmental concern is eutrophication. The constant discharge of wastewater into the lake will induce the water to become rich in dissolved nutrients, such as phosphates and nitrates, which encourage the growth of oxygen-depleting algae and other plant life. The algae, which thrive in the upper layers of the lake, create an anoxic environment that harms and can kill fish, plants and other organisms. Other environmental concerns include harsh odors and fly infestations.

The need for treatment is urgent because existing health and environmental risks are increasing. The population and industry in the region have been growing at a substantial pace. The cities surrounding the lake are becoming major urban areas, with a significant number of tourists during the summer months.

1.3 Proposed Objectives for the Region's Wastewater Management

In order to improve conditions in the region, a thorough system of wastewater treatment plants has to be put in place. This will ensure that water discharges into the Furnas Lake have the proper quality, achieving the very important goal of restoring the lake to its former conditions.

A main concern is that of providing a cost-effective and technically viable solution. An integral treatment system will not initially have to comprise both primary and secondary treatment. As a first step, Chemically Enhanced Primary Treatment, usually referred to by its acronym CEPT, is the best option to initiate wastewater treatment in this case. This technology will not only achieve treatment levels comparable to secondary treatment in terms of Total suspended solids and phosphorus removal, but also enable potential further expansions of secondary treatment plants to be less costly and more effective. In addition, CEPT effluent can be effectively disinfected, in contrast to conventional primary effluent, achieving the key goal of improving public health.

One of the region's main goals should be to reduce, and eventually eliminate, untreated wastewater released into the reservoir. Achieving this goal will help to preserve the local environment, and most importantly, to improve the standard of living throughout the region. With the primary objective of improving public health and the environment, a solution for the wastewater management for the region will be proposed. The city of Alfenas, located in the southeastern area of the lake, was selected for a study to design a Chemically Enhanced Primary Treatment plant as a first step towards the solution of the region's wastewater management problems.

1.4 The City of Alfenas

Alfenas is a rapidly growing city with a population of 66,000 inhabitants, located in the Brazilian state of Minas Gerais, about 250 km north of São Paulo (see Figure 1-3). The state of Minas Gerais has taken advantage of its mineral wealth to develop the second largest economy in Brazil, behind that of São Paulo. Covering an area of 849 km^2, Alfenas lies next to the FURNAS Lake, on its southeastern branch.

The topography around the city is mountainous, as is typical for the region. The downtown area is located at the top of a hill, while urban residential areas fan out in all directions. Six streams flow out to the west of the downtown area, from north to south: Pántano, Morada do Sol, Jardim de Boa Esperança, Chafariz, Estiva, and Trevo. These discharge into the Furnas Lake. Another stream, Coqueiral, runs towards the east. Finally, the Pedra Branca stream runs north south on the eastern side of the city (see Figure 1-4).

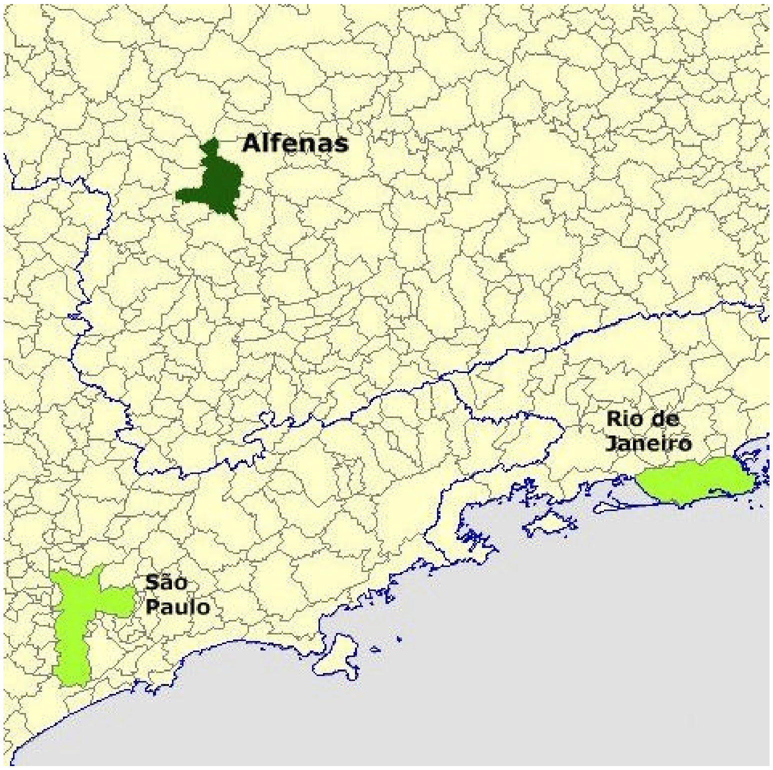


Figure 1-3: Map of Alfenas relative to São Paulo and Rio de Janeiro
(Source: IBGE, Brazilian Institute of Geography and Statistics, http://www.ibge.gov.br)

At present, Alfenas is constructing a citywide sewer collection system that, upon completion, will gather all the wastewater produced within city limits and conduct it to the projected wastewater treatment facilities.

All paved streets in the city have storm water and sewer collection piping running underneath them. The water collected through this system flows towards the streams previously enumerated, taking advantage of the natural gradient to transport the flow by gravity. Therefore, as the system stands today, all wastewater is being discharge into one of the streams, thus mixing with the natural spring water that runs along each.

After construction is completed, sewer main pipes will run along the streams, on each side of the storm water causeways, following the same path of the streams. Construction so far has covered 45% of the projected extension.

For this study, the Jardim de Boa Esperança stream was chosen because it drains the equivalent of 30% of the city's wastewater production and also the sewer system connecting to it is almost complete such that the sampled wastewater would be representative of the entire city.

A Chemically Enhanced Primary Treatment plant will be designed to serve the 20,000 inhabitants that currently discharge their wastewater into this basin. This will also serve as a modular installation that can be implemented in other sections of the city later.

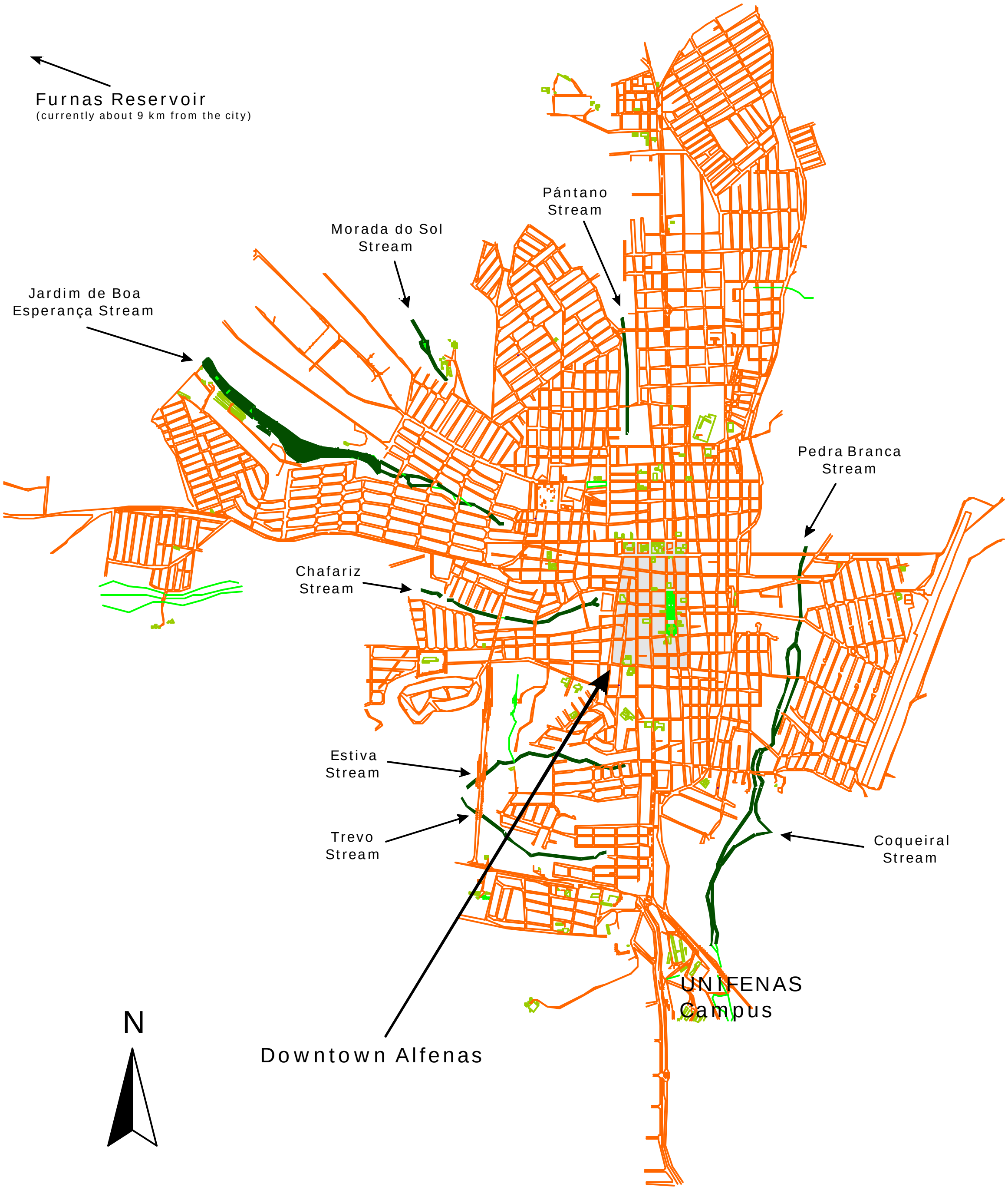


Figure 1-4: Map of Alfenas: city layout and streams

(Source: Alfenas City Hall, Office of Cartography)

1.5 CEPT in Brazil

Chemically Enhanced Primary Treatment is a technically appropriate and cost-effective solution to wastewater treatment in developing countries (Harleman and Murcott, 2001). As such, it has been successfully applied in Brazil for municipal wastewater treatment.

One interesting application of CEPT is that of the coastal resort city of Riviera de São Lourenço (Bourke, 2000 and Yu, 2000). This resort city, located 135 km north of São Paulo and characterized by a very environmentally aware attitude, has a permanent population of approximately 20,000 inhabitants. During the summer months, tourists from all of Brazil flood the city, elevating population to 80,000 or more. This is one of the very few Brazilian coastal cities that discharge their treated wastewater into a river, in this case the Itapanhaú, instead of directly into the ocean (http://www.rivieradesaolourenco.com).

To cope with the contrasting seasonal variations, a CEPT unit was constructed to support the existing wastewater treatment, comprised of one anaerobic lagoon, three facultative lagoons and a chlorination chamber (see Figure 1-5 and Figure 1-6). The CEPT unit became operational in January 2000. The chemical dosing used is a combination of 50 mg/L of $FeCl_3$ and 0.5 mg/L of a synthetic anionic polymer. With this treatment in place, the plant is able to handle an average flow of 8,400 m^3/day, reducing total suspended solids (TSS) by 85% and biochemical oxygen demand (BOD) by 60%.

Figure 1-5: CEPT treatment implemented at Riviera de São Lourenço
(Source: Sobloco Construction Company, http://www.sobloco.com.br)

Figure 1-6: Detail of the CEPT tanks at Riviera de São Lourenço
(Source: http://www.rivieradesaolourenco.com)

A similar application of CEPT was studied for the city of Tatui, also in the state of São Paulo. The city possesses a very poorly maintained lagoon system (see Figure 1-7), and the local proposal was to add aerators to these lagoons in order to increase their efficiency. A group of MIT Master of Engineering students proposed retrofitting the facility with a CEPT unit (Harleman, et.al., 1999). Through bench scale studies, it was found that adding CEPT, either in separate mixing tanks or in a CEPT pond, would eliminate the need for aerators while providing a technically sound solution (Gotovac, 1999 and Chagnon, 1999).

Figure 1-7: Lagoon system at Tatui, Brazil
(Source: Susan Murcott)

CEPT has also been applied in two wastewater treatment plants for the city of Rio de Janeiro (Harleman and Murcott, 2001) and has been studied for application in Rio de Janeiro, Ipiranga (see Figure 1-8) and São Paulo. Cost analysis for all these bench scale and pilot plant studies showed that CEPT offers an optimal solution to increase plant capacity without need of major capital investments and, more importantly, without disrupting plant operations.

Figure 1-8: Detail of the pilot-plant chemical dosing system at Ipiranga (Source: Susan Murcott)

2. CEPT process theory

2.1 Coagulation and Flocculation

Low-dose Chemically Enhanced Primary Treatment entails the use of additives in the treatment of wastewaters to aid the settling of solid particles suspended in water. This takes place by two physicochemical processes: coagulation and flocculation.

Coagulation is achieved by adding multi-valent cationic metals, preferably in the form of salts, such as $Al_2(SO_4)_3$ and $FeCl_3$, or low molecular weight cationic polymers. The purpose is forming denser, more compact, solid masses gathered by electrostatic forces. In the case of metallic salts, typical concentrations range from 5 to 40 mg per liter (ppm) of water to be treated (Ødegaard, 1998), while cationic polymers are usually dosed in ranges from 0.1 to 5 ppm. Energetic mixing is needed for the cationic additive to bind to the suspended solids in the wastewater. Therefore, the cationic coagulant is usually added as far upstream in the process as possible or dosed in a contact chamber equipped with mechanical mixers.

Flocculation takes place after adding high molecular weight anionic polymers, which, again by electrostatic forces, group the coagulated particles into larger structures. Flocs, being much larger particles, settle faster by gravity than suspended solids alone, as governed by Stokes' Law. This law states that particles will settle through any given fluid by gravity forces with a speed that is directly proportional to the square of their size. Slow mixing is typically used to assist in the flocculation process.

The exact combination of salts and polymers is different for each stream of wastewater, requiring detailed field-testing to determine the appropriate dosage in each case. Figure 2-1 schematically shows the processes of coagulation and flocculation.

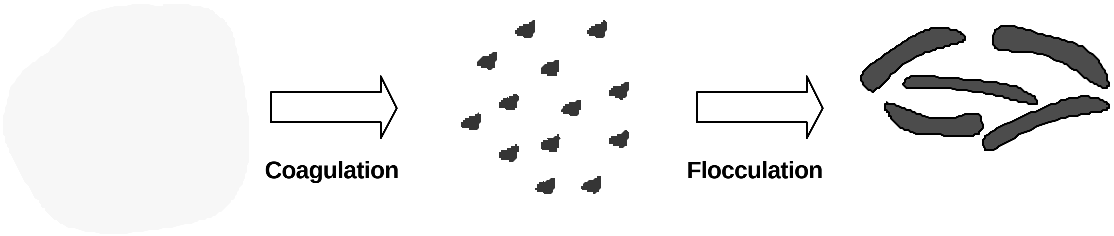


Figure 2-1: Graphical Depiction of the Coagulation and Flocculation Processes

2.2 Process efficiency

Contrasting with secondary treatment, CEPT yields comparable Total suspended solids (TSS) removal rates. Biochemical Oxygen Demand (BOD) removal is lower, but efficient in terms of cost. Phosphorus (P) removal rates are remarkably higher when using $FeCl_3$, due to its precipitation as $Fe_2(PO_4)_3$. All of this is achieved while generating low volumes of sludge. These results for CEPT are shown in Table 2-1, which compares removal efficiencies and sludge production for primary treatment, secondary treatment and CEPT.

Table 2-1: Comparison of Removal Rates and Sludge Production

Treatment Type	TSS Removed	BOD Removed	P Removed	Sludge from TSS	Sludge from Chemicals or Biomass	Total Sludge
Primary	60 %	35 %	20 %	X	0	X
Chemically Enhanced Primary ($FeCl_3$ + anionic polymer)	80 %	57 %	85 %	1.33·X	0.12·X	1.45·X
Primary + Biological Secondary	85 %	85 %	30 %	1.42·X	0.48·X	1.90·X

Source: CEPT results from San Diego, CA – Pt. Loma plant operational data (Langworthy, 1990), Secondary treatment results from Black & Veatch, Inc., Boston, MA. January 1998. Residual Management Facilities Plan: Draft Characterization of Residuals, Suppl. Rep. No. 1. Prepared for MWRA.

From the table, it is clear that CEPT offers optimal removal rates for TSS and P per unit of sludge produced where "X" is the standard raw sludge production for conventional primary treatment. Another important factor is that after CEPT treatment, water can be effectively disinfected to produce an effluent suitable for discharge into natural bodies of water.

2.3 Typical CEPT process flow

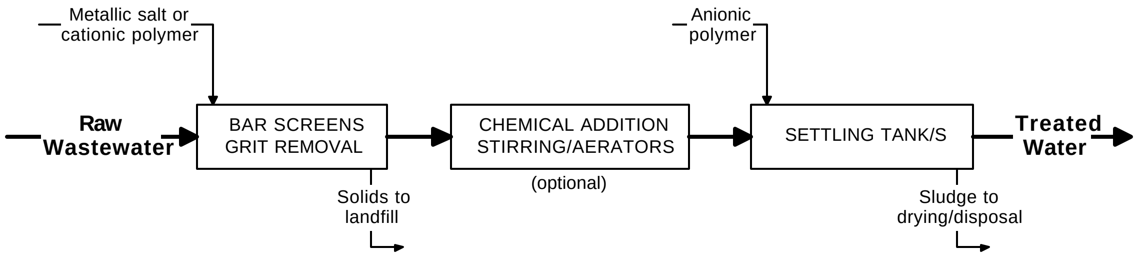


Figure 2-2: CEPT Process Flow Diagram

Figure 2-2 depicts typical unit operations and processes for CEPT. Larger particles are removed first by letting water flow through bar screens and a grit removal chamber. For chemical mixing, there are two options. The first is to inject the appropriate dosage of metallic salt (usually $FeCl_3$) or cationic polymer at the head of the plant, before the flow passes through the bar screens. The second option is to use a chemical mixing chamber, assisted with mechanical mixers or aerators. Water then flows over to the settling tank, where the anionic polymer, if necessary, will be injected, and as the flow progresses through the tank, flocs will settle out of the water column. Residence times are in the range of 5-10 minutes for chemical mixing and 1 hour for settling, depending on chemical dosage, flow rate and water constituents. Sludge is removed from the settling tanks, and the supernatant is ready for disinfection, secondary treatment or final disposal.

2.4 Advantages of CEPT

The foremost advantage of using CEPT instead of conventional primary treatment is that settling tanks required for the first are approximately half the size of those required for the second. Since surface overflow rates for CEPT can double those used for conventional primary treatment, for the same volumetric flow of wastewater, the required surface area for CEPT will be approximately half that of conventional primary treatment. This translates into significant capital cost savings.

Furthermore, a CEPT system can be more effectively operated and maintained than an activated sludge system because it allows for greater resilience, and reliability. CEPT systems remain functional and can maintain optimal removal efficiencies in the presence of a broad range of waste stream compositions and temperatures, avoiding biological upsets due to the formation of toxic materials, a characteristic issue with biological secondary treatment units. Chemical dosages can conveniently be altered to match changes in loading and composition, allowing for greater reliability and flexibility.

A CEPT plant can also be easily expanded to process larger flow volumes, if necessary, by increasing chemical dosing and adding additional tanks. Such upgrades in a CEPT plant have minimal negative impacts on system performance, as it was demonstrated in the Riviera de São Lourenço project (see section 1.5, page 18). Moreover, conventional primary treatment plants can be retrofitted with CEPT technology, effectively doubling the plant's previous capacity. CEPT tanks can also be easily added to any existing facility, as they tend to be small and easy to accommodate.

3. Field study procedures and results

3.1 Introduction

Upon invitation from José Wurtemberg Manso, mayor of the city of Alfenas, a field study was conducted between January 4 and January 26, 2002. This field study was comprised of bench-scale testing of CEPT and lab analysis of raw wastewater, treated water, sludge and lake water. The objectives of this testing were:

- Determine the optimal combination of chemicals for treatment
- Confirm efficiency of typical overflow rates for CEPT
- Gather chemical analysis data to back up these two findings
- Study sludge management options (Stout, 2002)
- Monitor reservoir state (Fateen, 2002)

For this purpose, the city provided access to the laboratory facilities of the Hydric Resources Environmental Research Laboratory, lead by Prof. Eduardo Tanure, at UNIFENAS (Alfenas University).

The following sections describe the sampling method and location, the laboratory procedures for chemical analysis and the procedures for bench-scale testing (jar testing). A summary and analysis of the most relevant results follows.

3.2 Sampling method and location

Samples were taken from a sewer runoff at the Jardim de Boa Esperança stream (see Figure 3-1). Since the sewer system is not yet completed, the sampling point was selected to be at the place where currently built sewers meet with the stream. This is also the point where the storm water causeway ends for this stream (see Figure 3-2).

The location of the sampling point (see Figure 3-3) was downstream enough to contain a representative composition of the wastewater that would reach the end of the stream, at the point where the proposed plant would be constructed (see section 4.4, page 59). In addition, accessibility was considered, as the sampling point was located in public property and easily accessible from the road. Sampling took place usually during the morning, typical time of collection ranging from 8 to 11:30 am.

Two 20-liter plastic bottles were filled with wastewater at this source, and carried to the lab covered in black plastic paper bags, to avoid adverse biological and chemical reactions that might occur upon exposition to UV radiation.

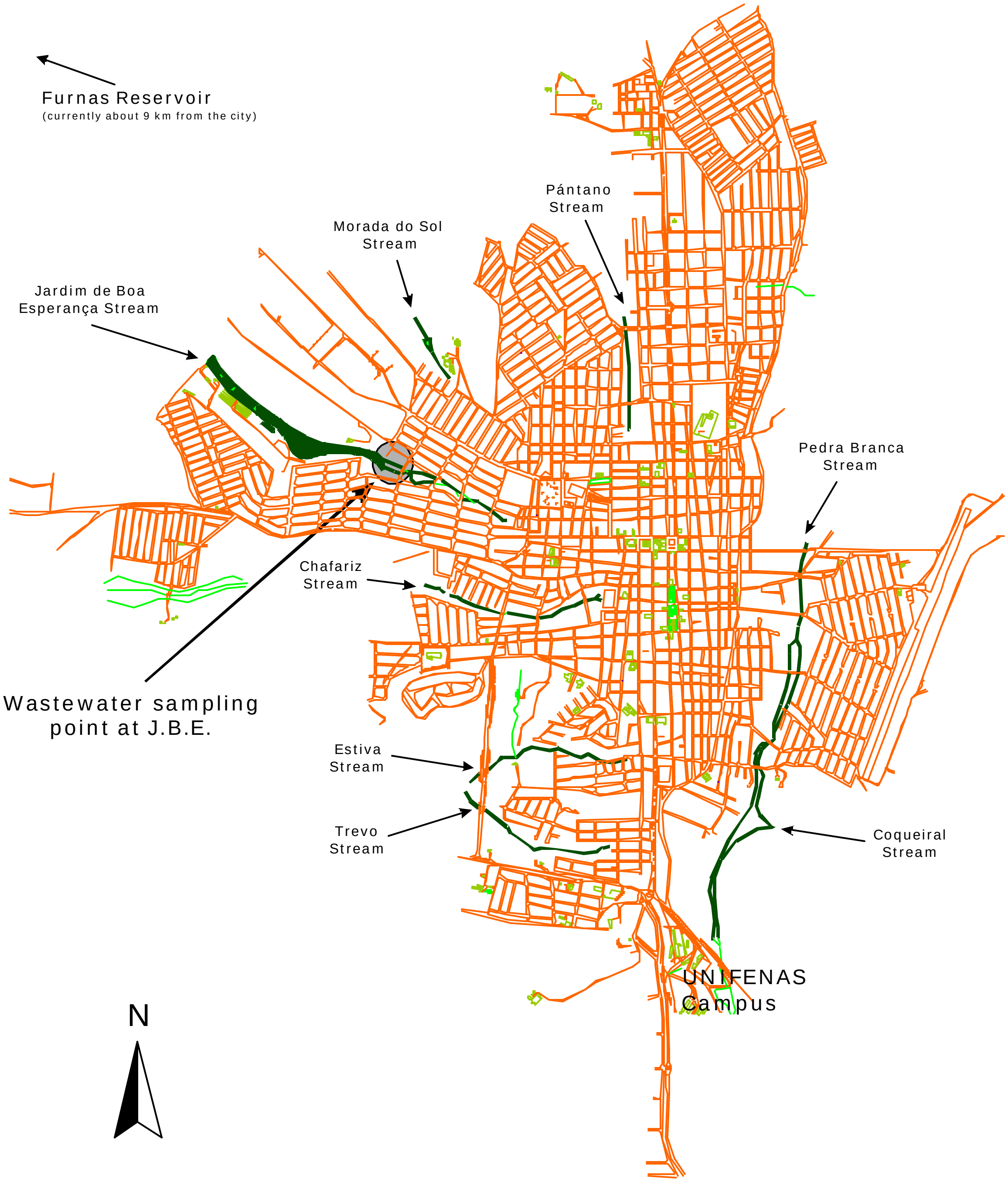


Figure 3-1: Map of sampling area, sampling site enclosed in circle (Source: Alfenas City Hall, Office of Cartography)

Figure 3-2: Storm water channel, image taken at the source of the Jardim de Boa Esperança stream

Figure 3-3: Sampling point at the Jardim de Boa Esperança stream, wastewater was collected from underneath the bamboo branches

3.3 Lab analysis procedures

The following section describes the chemical analysis procedures used during the field study in Alfenas.

3.3.1 Total suspended solids

Total suspended solids were measured according to the procedures indicated in Standard Methods # 2540D. The vacuum apparatus used was composed of a membrane filter funnel and a suction flask connected to an electric air pump. Glass fiber filters, 5 cm in diameter with a pore size of 1 μm, were used. An electric oven was used to dry the samples. During the first week, between Jan 9 and 11, the oven used for this purpose was malfunctioning, and maintained temperatures varying from 60 to 110 ^{o}C. At the beginning of the second week, the oven was replaced for another that was kept constantly at 105 ^{o}C, according to the procedure. For storage and transportation, samples were placed in aluminum weighing dishes and kept in a dessicator.

Glass fiber filters were cleaned before use by filtering three 20 mL portions of distilled and deionized water through them. They were then placed in aluminum weighing dishes and put to dry in the oven for 60 minutes. After cooling to room temperature in a dessicator, the ready-to-use, also referred to as "blank," filters were weighed. The weight of each filter plus the weighing dish was recorded.

To carry out the measurement, a blank filter was placed in the apparatus and one 20 mL volume of distilled and deionized water was run through. Then, a well-mixed volume of sample water, ranging from 10 to 40 mL, was extracted using a pipette and let flow through the filter. Two 20 mL volumes of distilled and deionized water followed to ensure all particles were properly washed from the flask's walls. The filters were then placed back into their aluminum weighing dishes and in the oven for drying. After 60 minutes of drying in the oven, samples were put in the dessicator to cool down and were then weighed. Again, weight of both the filter and the weighing dish were recorded.

To calculate the total suspended solids in a sample, the following formula was used:

$$\text{mg total suspended solids} / \text{L} = \frac{(\text{sample weight} - \text{blank weight}) \cdot 1000}{\text{sample volume, mL}}$$

Equation 3-1: Calculation of total suspended solids

3.3.2 Chemical oxygen demand

Chemical oxygen demand (COD) was measured using the dichromate Hach Method number 8000, which is approved by the U.S. Environmental Protection agency. A Hach model DR/4000 spectrophotometer was used to read the samples. Standard Hach COD digestion vials for the 0-1500 mg/L range were used (Cat. No. 21279-15).

Samples were well mixed and a 2 mL portion was taken using an automatic pipette and injected into the COD vial. Samples were then placed in the pre-heated COD reactor and were left to digest for 120 minutes. After cooling, the COD content was measured using the spectrophotometer.

3.3.3 BOD-COD correlation

COD was chosen over the lengthy biochemical oxygen demand (BOD) analysis because of time constraints. BOD analyses require three or five days of digestion while COD analyses require only two hours. However, regulations are always referred to BOD levels and a proper correlation needs to be established between the two.

To obtain this relationship, the values of COD and BOD from wastewater samples from Alfenas were used. These samples were taken as part of the Furnas II project, led by Professor Eduardo Tanure of UNIFENAS (Alfenas University) from four key points around the city where wastewater streams are mixed with fresh water natural springs. Seventy samples, taken between 1996 and 1999, were used to obtain the correlation.

The following graph (Figure 3-4) shows a scatter plot for the data and the regression line traced over them. Correlation was very high, with an $R^2 = .96$, confirming the relationship and providing a link between the two parameters.

For samples that had a COD value of less than 200 mg/L, the regression line shows a lower slope, but still within the expected BOD/COD ratio of 0.4 to 0.8 (Metcalf & Eddy, 1991). Therefore, the correlation is proper for values of COD ranging from 250 to 1100 mg/L, which are typical for the raw wastewater found in Alfenas.

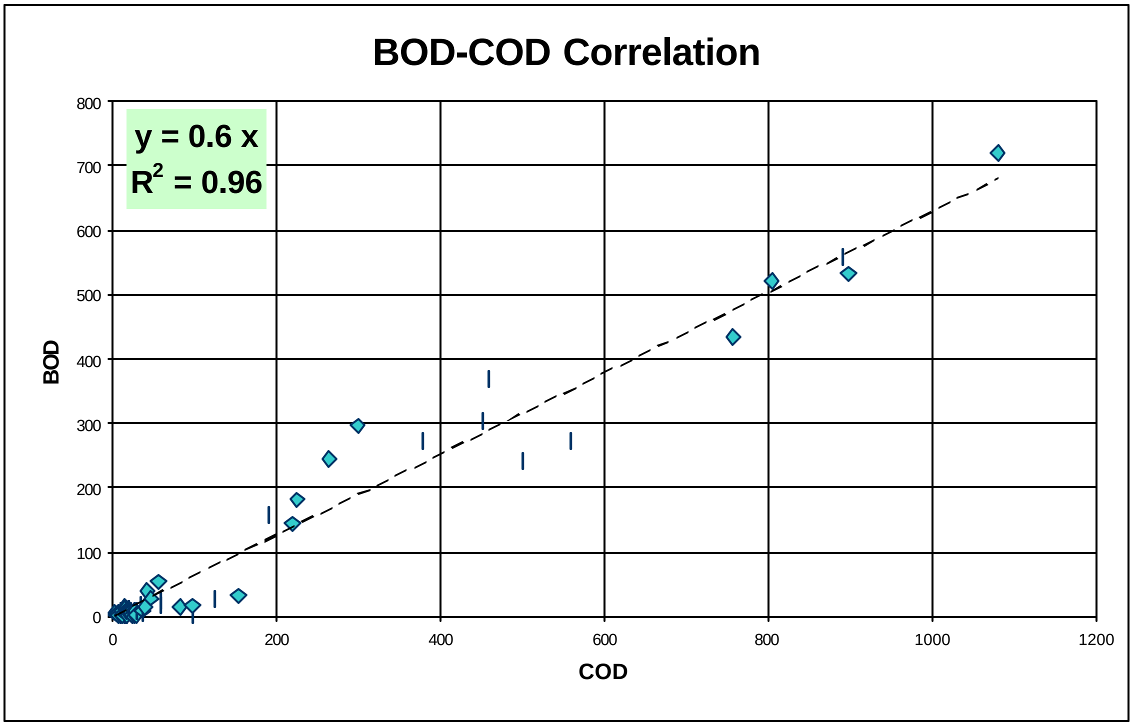


Figure 3-4: COD-BOD correlation scatter plot

From the regression curve, it is found that BOD could be calculated from COD data by applying a factor of 0.6 to the COD value. To confirm this relationship, two raw wastewater samples were analyzed for both COD and

BOD, using Dr. Tanure's methods. These values, shown in the table below, confirm the relationship within reasonable analysis error.

Table 3-1: BOD and COD results for two wastewater samples

Sample	BOD_3 (mg/L)	COD (mg/L)	BOD/COD
1	164	282	0.57
2	175	257	0.68

It will be assumed that removal rates for COD and BOD will also have a linear relationship, thus treatment efficiencies for COD removal discussed in section 3.6, page 40, will also apply to BOD removal.

3.3.4 Turbidity

Turbidity for water samples was measured using a Hach 2100 series turbidimeter. Standard Hach 20 mL vials were filled with the sample and measured using the NTU scale.

3.3.5 Total and fecal coliforms

To measure total and fecal coliforms, the multiple-tube method 9221 of the Standard Methods was used. Digestion mediums were inoculated with a drop of sample, with dilution ranging from 10^{-3} to 10^{-7} and left to digest in an oven set at 35 °C for 48 hours. Tubes showing positive reaction, evidenced by bubbling, were re-inoculated in fecal coliform mediums and heated in water bath at 40 ^{o}C for 24 hours, after which a second reading was taken.

3.3.6 Phosphorus

To measure phosphorus levels, the Hach disc colorimeter method for orthophosphate was used in the 0-50 mg/L range. 10 mL of sample were mixed with one reaction packet (Cat. No. 25080-50) and left to react for 5 minutes, then the coloring was compared with the standardized disc to obtain the reading. All raw wastewater samples showed orthophosphate (also referred to as "phosphorus" throughout this thesis) content of 10 mg/L or less. Upon treatment, the supernatant showed values below detectable levels, i.e. less than 2 mg/L, in the cases where $FeCl_3$ was used. For other chemicals, treated water contained less than 4 mg/L. Most jar testing samples were not tested for phosphorus, see Appendix A for details on the ones that were tested.

3.4 Raw wastewater characteristics

From the 34 samples of raw wastewater taken from the Jardim de Boa Esperança stream, the average value for the key parameters described in the previous section were:

Table 3-2: Raw wastewater characteristics summary

Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)	Fecal Coliforms (MPN/100 mL)

191	**215**	**494**	**6.9**	**7.6**	**$8\cdot10^6$**

3.5 Jar testing procedures

Jar testing was conducted using a Kemwater Flocculator 2000 kit (see Figure 3-5). The kit consists of six cylindrical 1 L jars with agitators that are controlled from a central computerized unit. Full programming capabilities allow the establishment of four treatment stages:

- High-speed mixing (60 seconds)
- Low-speed mixing (5 minutes)
- Settling with no mixing (varied according to desired overflow rate)
- Secondary high-speed mixing (not used)

For the purposes of CEPT jar testing, the rapid mixing stage was set at 100 RPM for 60 seconds and slow mixing was set at 40 RPM for 5 minutes. Settling time varied from 1,5 to 10 minutes, according to the overflow rate desired. The secondary rapid mixing was not used.

For jar tests using only one chemical as coagulant, injection occurred after 30 seconds of high-speed mixing. For combined coagulant plus flocculant tests, the coagulant was injected at 30 seconds of rapid mixing and the flocculant at 60 seconds, when the mixing changed from rapid to slow.

Figure 3-5: Jar-testing equipment used on the field study

The basis for relating batch jar-testing results to a continuous flow treatment system is that the overflow rate for both processes is the same. The efficiency of the coagulation and flocculation processes are proportional to the time the chemicals are in contact with the water, so it is possible to extrapolate data from jar tests and apply it to plant design. For a continuous-flow settling tank, the residence time can be calculated as the ratio of its volume to the flow rate of water:

$$t_R = \frac{L \cdot W \cdot H}{Q}$$

Equation 3-2: Residence time in a CEPT tank

Where t_R is the residence time, L is the length, W is the width, H is the water depth and Q is the volumetric flow rate. The surface overflow rate (SOR) is correlated with the percent removal of particulate material in a settling tank, and it can be expressed as:

$$\mathrm{SOR} = \frac{Q}{L \cdot W} = \frac{H}{t_R}$$

Equation 3-3: Surface overflow rate for a CEPT tank

From the jar tests, we define a value for settling depth and time within the jar, h and t_J respectively, from which we can express:

$$\mathrm{SOR} = \frac{h}{t_J}$$

Equation 3-4: Surface overflow rate for jar test

All samples were taken from an outlet located 6 cm below the surface of the water, so h = 6 cm. Residence time in the jar, t_J, was varied to obtain different SOR. For instance, for a $t_J = 1.5$ min, the corresponding SOR would be:

$$\mathrm{SOR}_{1.5\,\mathrm{min}} = \frac{6\,\mathrm{cm} \cdot {}^{0,01\,\mathrm{m}}\!/\!_{\mathrm{cm}}}{1.5\,\mathrm{min} \cdot {}^{\mathrm{day}}\!/\!_{24 \cdot 60\,\mathrm{min}}} = 57.6\,\frac{\mathrm{m}}{\mathrm{day}} \approx 60\,\frac{\mathrm{m}}{\mathrm{day}}$$

Equation 3-5: Surface overflow rate for jar test at t_J = 1.5 min

During the test, observations were recorded as to the floc size, change in color or turbidity of water and speed of settling. These observations were used as support data together with lab analysis results.

Samples of supernatant treated water were collected in clean, clear plastic bottles, properly labeled so they could be unequivocally identified. Bottles were immediately stored in a Styrofoam cooler, to avoid temperature and sunlight exposure from promoting adverse reactions in the water.

The chemicals used for jar testing included alum (aluminum sulfate), ferric chloride, synthetic cationic, anionic and neutral polymers, and Tanfloc, a locally available organic cationic polymer made from Acacia Mearnsii bark extracts. Tanfloc is a product that has been extensively used for water treatment, with very satisfactory results (http://www.tanac.com.br/ingles/index.html).

3.6 Discussion of relevant jar testing results

The data presented next highlights the bench-scale jar testing results that are most relevant to the selection of chemical dosing and the confirmation of the appropriate surface overflow rate (SOR) for treatment.

The target SOR was set at 60 m/day, about twice the design value for conventional primary treatment. Additional samples were taken at 30 m/day, to get an idea of the potential of each chemical.

3.6.1 Selection of chemical dosing

First, jar testing explored the use of a single chemical as coagulant. The chemicals tested were: alum, $FeCl_3$, Tanfloc and a neutral synthetic polymer. For the first three coagulants, performance can be assessed in the following graph that compares their COD removal efficiency:

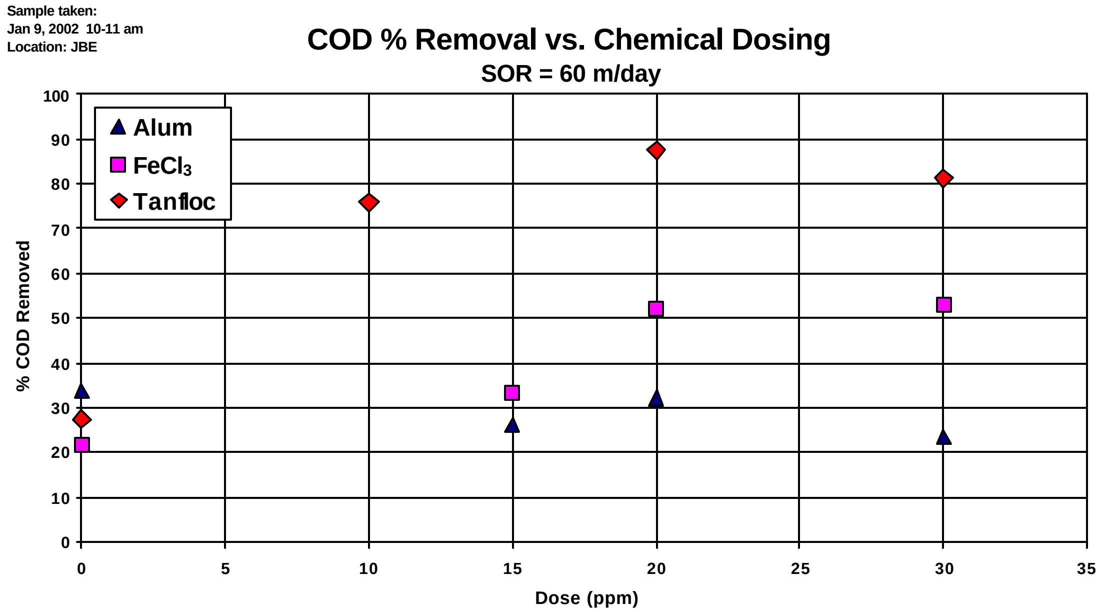


Figure 3-6: Coagulant selection graph

From Figure 3-6, Tanfloc results as the best option for coagulant and alum clearly shows poor performance.

Next, several combinations were tested, using alum, $FeCl_3$ and Tanfloc as coagulants and comparing their performance with several synthetic polymers (anionic, cationic and neutral) and Tanfloc as flocculants. Performance of Tanfloc was comparable to that of synthetic polymers, but for cost reasons, these were dismissed. Average costs of synthetic polymers are around 5 USD per kg, while the cost of Tanfloc is only 0.93 USD per kg. To obtain comparable results, a dosage of 5 ppm for synthetic polymers is required, while only 10 ppm of Tanfloc were needed, thus cost efficiencies remained favorable for the latter.

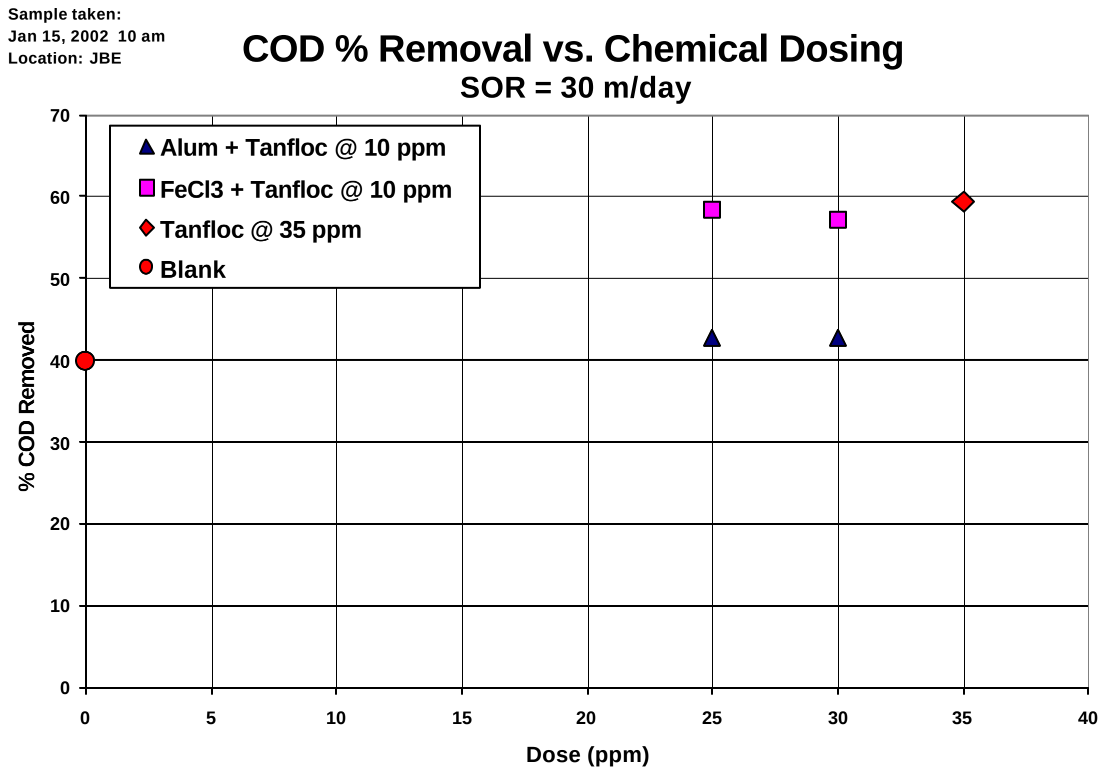


Figure 3-7: Flocculant selection graph

Figure 3-7 shows the high efficiency of Tanfloc, both as a flocculant when using $FeCl_3$ as the coagulant, and as a coagulant on its own. Performance of alum remained poor. From these results, it was concluded that the two best options for treatment are:

- $FeCl_3$ as coagulant (30 ppm) and Tanfloc as flocculant (10 ppm)
- Tanfloc as coagulant (30 ppm)

3.6.2 Results for option 1: $FeCl_3$ 30 ppm and Tanfloc 10 ppm

A summary of jar testing of this chemical combination shows typical results expected for CEPT, with turbidity removal of 60%, TSS removal of 70%, COD removal of 64% and phosphorus removal over 90%.

Table 3-3: Summary of jar testing results for $FeCl_3$ + Tanfloc

30 m/day	Turbidity % Removal	TSS % Removal	COD % Removal
Average	67	77	64
Max	86	89	74
Min	46	70	57
Number of samples: 6			

60 m/day	Turbidity % Removal	TSS % Removal	COD % Removal
Average	55	65	64
Max	57	66	71
Min	53	65	56
Number of samples: 2			

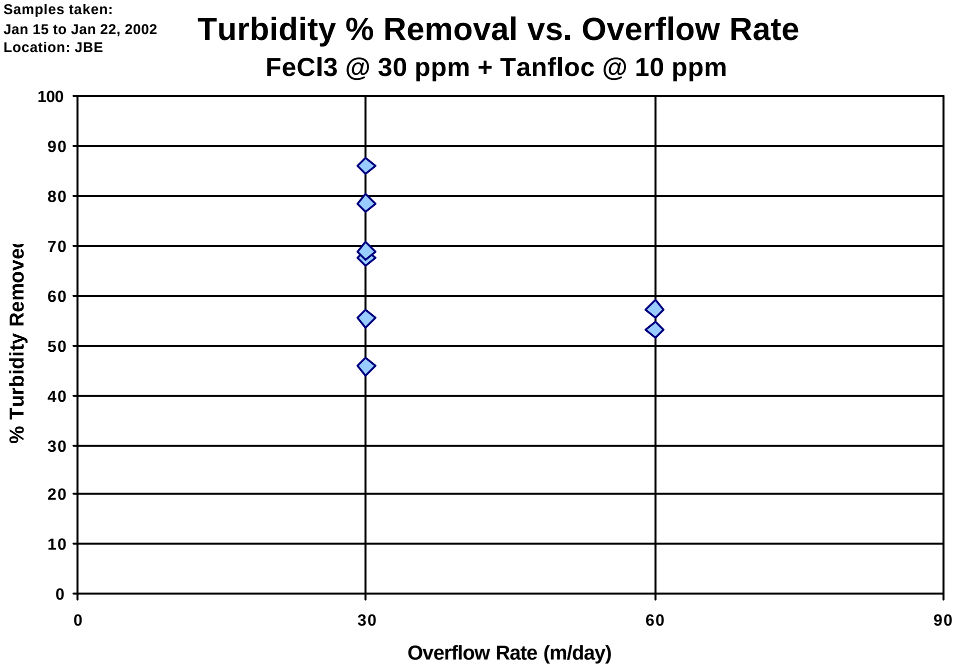

Samples taken:
Jan 15 to Jan 22, 2002
Location: JBE

Figure 3-8: Turbidity removal efficiencies for $FeCl_3$ + Tanfloc

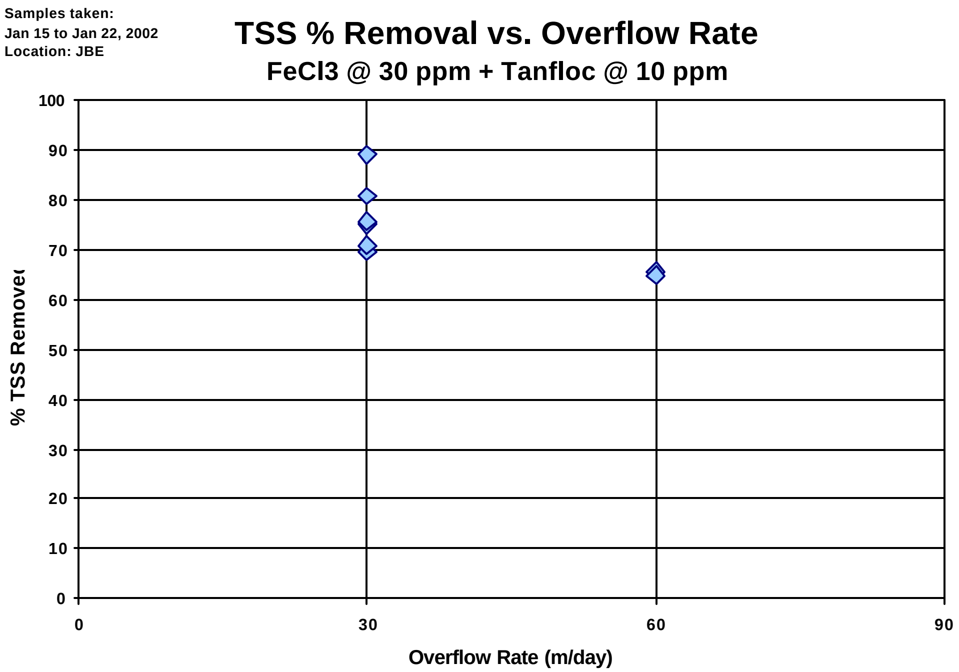


Figure 3-9: TSS removal efficiencies for $FeCl_3$ + Tanfloc

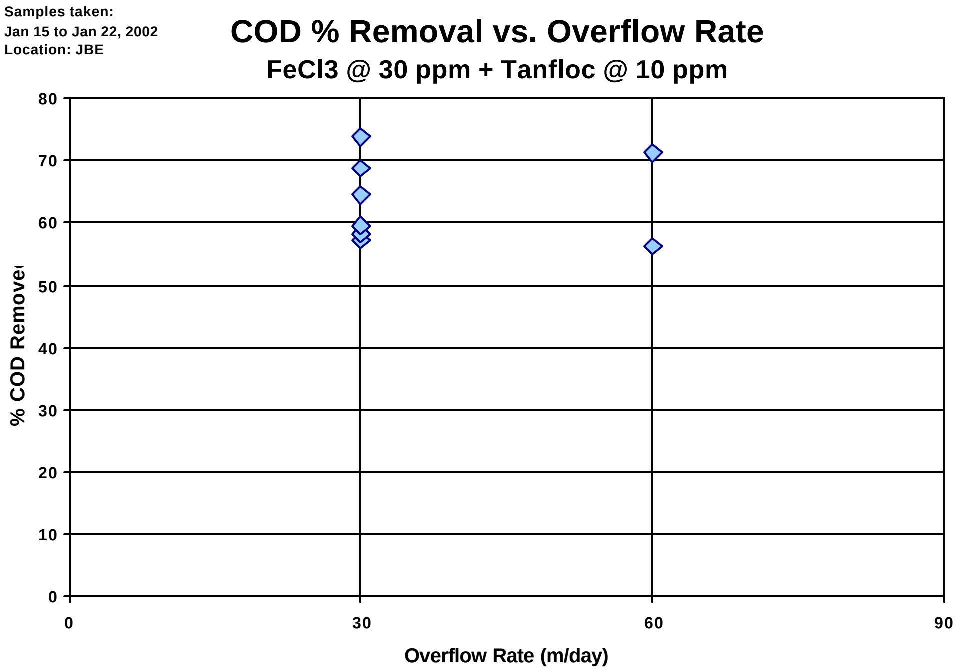


Figure 3-10: COD removal efficiencies for $FeCl_3$ + Tanfloc

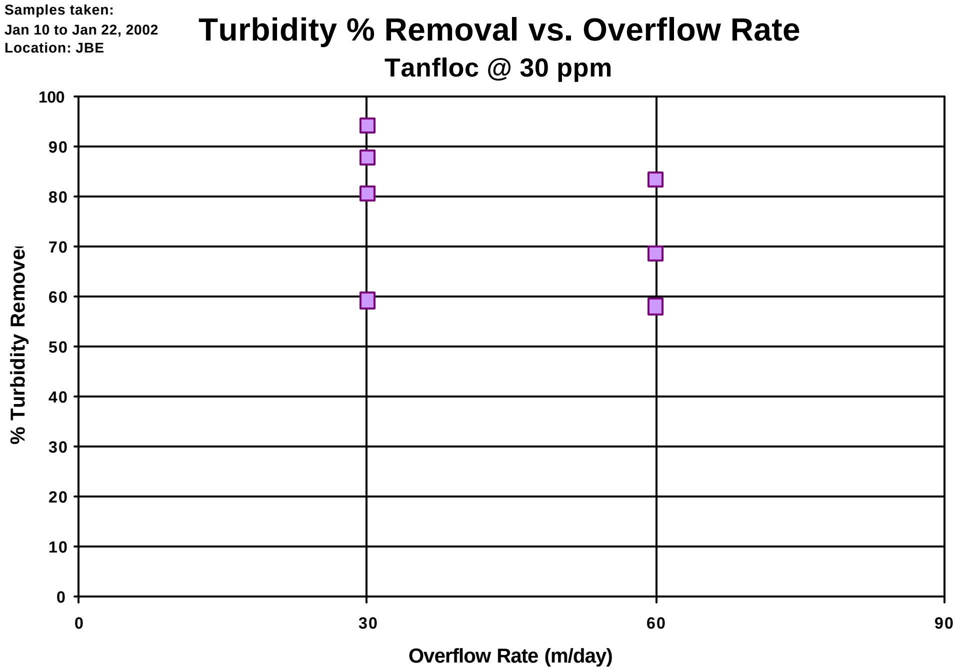
3.6.3 Results for option 2: Tanfloc 30 ppm

Results of jar testing for this option show removal efficiencies comparable to those of the previous option, with turbidity removal of 75%, TSS removal of 80%, COD removal of 55% and phosphorus removal around 65%.

Table 3-4: Summary of jar testing results for Tanfloc

30 m/day	Turbidity % Removal	TSS % Removal	COD % Removal
Average	80	93	46
Max	94	98	51
Min	59	85	40
Number of samples: 4			

60 m/day	Turbidity % Removal	TSS % Removal	COD % Removal
Average	70	68	67
Max	83	85	81
Min	58	50	54
Number of samples: 2			


Samples taken:
Jan 10 to Jan 22, 2002
Location: JBE

Turbidity % Removal vs. Overflow Rate

Tanfloc @ 30 ppm

Figure 3-11: Turbidity removal efficiencies for Tanfloc

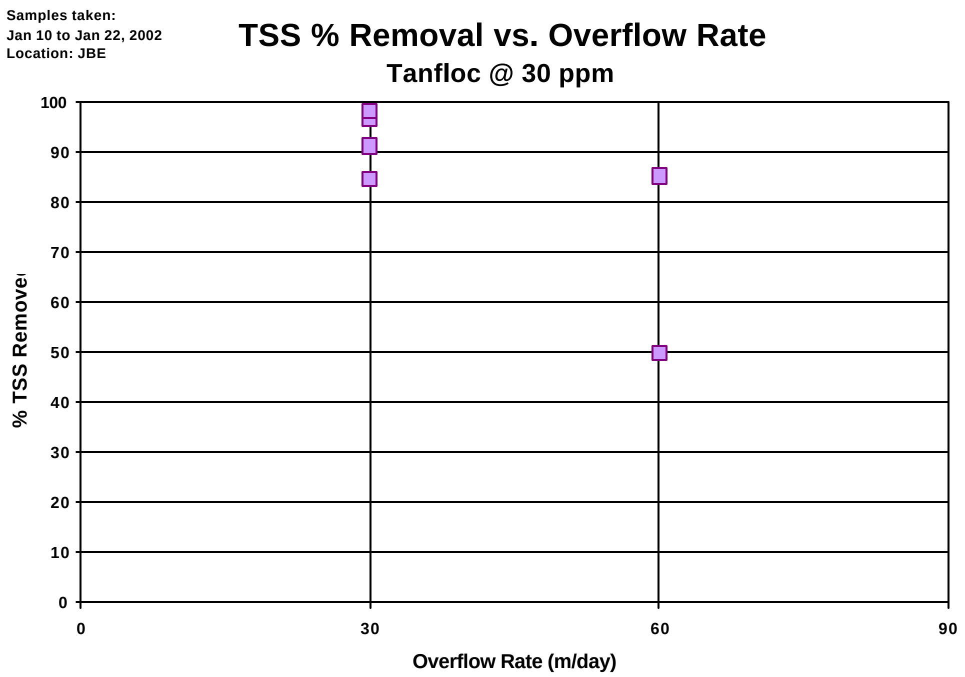


Figure 3-12: TSS removal efficiencies for Tanfloc

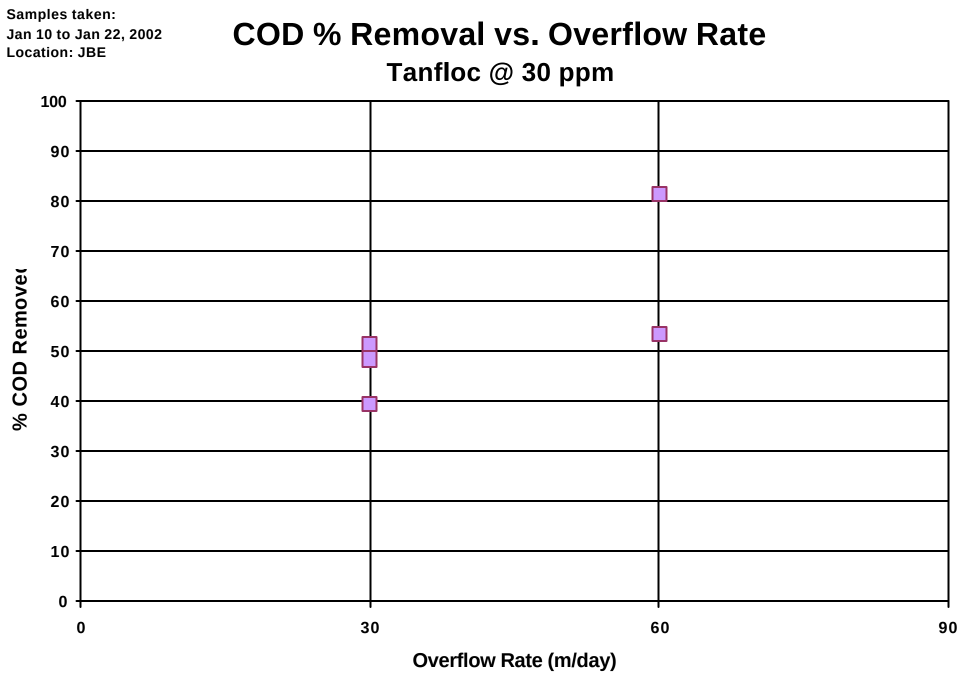


Figure 3-13: COD removal efficiencies for Tanfloc

3.6.4 Analysis of results

These results validate the selection of 60 m/day as the target overflow rate for the design of the proposed plant. It should be noted that while the data presented offers a good sense of what the expected efficiency of the plant will be, the limited amount of data points obtained indicate that the proposed chemical dosing will require adjustments, which will be a part of the plant's startup procedures.

In general, it is expected that removal rates at higher overflow rates be less than at lower overflow rates, since particles will have more time to settle out when the overflow rate is lower. This proves true in most cases for the data presented, but the COD results for Tanfloc alone show that removal rates at 60 m/day exceeded those at 30 m/day. No strong conclusions can be drawn in this case, since the amount of information is limited to two data points for 60 m/day and three data points for 30 m/day. However, except for the single point indicating 81% removal of COD for Tanfloc at 30 ppm, all others remain around 48% (±8%), indicating that expected removals for COD using Tanfloc alone should be around 50%. Comparing these results with those for $FeCl_3$ + Tanfloc, for which COD removal rates were around 64%, it can be concluded that the combination of chemicals offers better removal efficiency in terms of COD, and thus of BOD, as assumed in section 3.3.3, page 33.

Total suspended solids removal for $FeCl_3$ + Tanfloc at 60 m/day was 65%, while removal with Tanfloc alone was 68% at the same overflow rate. This means the TSS removal efficiencies for both options are comparable under expected operational conditions. In addition, Tanfloc alone demonstrated higher efficiency in TSS removal at 30 m/day, 93% compared with 77% of the $FeCl_3$ + Tanfloc. Treating wastewaters with $FeCl_3$ produces inorganic precipitates, e.g. ferric hydroxides and ferric phosphates, and thus increases the amount of solids formed in the process, leading to lower TSS removal efficiencies. Tanfloc, being a natural polymer, is not expected to generate as many precipitates. In conclusion, TSS removal efficiencies for the two options are comparable, with a slight advantage towards the Tanfloc alone option.

In the case of turbidity, one important factor to be considered when analyzing results is that $FeCl_3$ not only produces a wider variety of solid precipitates, some of which are not soluble, but also generates a yellow coloring in the water. These two factors contribute to less efficiency in turbidity removal for $FeCl_3$ + Tanfloc, around 55% at 60 m/day, compared to Tanfloc alone, around 70% at the same overflow rate. Visually, effluent treated with Tanfloc was much clearer after 10 minutes of settling than effluent treated with $FeCl_3$. Thus, it can be concluded that turbidity removal efficiencies for Tanfloc alone are higher than for $FeCl_3$+Tanfloc.

Finally, removal of phosphorus, a key parameter for environmental concerns such as eutrophication, was around 90% for $FeCl_3$+Tanfloc and only around 65% for Tanfloc alone. As explained above, $FeCl_3$ produces ferric phosphates as precipitates, which enhances the removal efficiency for phosphorus, while Tanfloc does not possess this quality. Results indicate that $FeCl_3$+Tanfloc is the best option in terms of phosphorus removal.

In conclusion, of the four parameters selected for comparison, the $FeCl_3$+Tanfloc option was shown to perform better in terms of phosphorus and COD removal, while Tanfloc alone was more efficient for turbidity. TSS removal was comparable for both options.

3.6.5 Selection of best option for treatment

Aside from removal efficiencies, a major comparison point between the two options for chemical dosing is that of cost. While using two chemicals entails a higher capital cost, due to the added infrastructure, operational costs for Tanfloc alone are much higher, because it is about three times as expensive as $FeCl_3$. The following table summarizes data for approximate value of plant equipment in USD. Most information was obtained by verbal communication with several manufacturers and design engineers. This data is presented to support the cash flow calculations and to give an idea of the overall costs of a CEPT plant. Labor and other construction costs are neglected.

Table 3-5: Estimate of plant capital costs

Equipment	**Approximate Price (USD)**
Bar screens with manual cleaning	7,200
Grit removal chamber, vortex type	1,600
Parshall flume, prefabricated acrylic	1,500
Magnetic flow meter	700
Programmable logic controller	100
PVC storage tank for $FeCl_3$	400
PVC storage tank for Tanfloc	200
PVC storage tank for NaClO	200
Diaphragm dosing pumps (three)	3x 300
CEPT settling tanks	15,000
Scum/sludge scrapers	25,000
Disinfection chamber	5,000
Piping and accessories	2,200
TOTAL	**60,000**

Per kilogram, $FeCl_3$ costs 0.3 USD while Tanfloc costs 0.93 USD (converted from Brazilian currency at official exchange rates of the Brazilian National Bank during January, 2002). According to the dosing for the $FeCl_3$+Tanfloc option, the daily mass flow of each chemical would be:

$$\text{Daily mass flow of } FeCl_3 = 30\,\tfrac{mg}{L}\cdot 3600\,\tfrac{m^3}{day}\cdot 1000\,\tfrac{L}{m^3}\cdot\tfrac{kg}{10^6 mg} = 108\,\tfrac{kg}{day}$$

$$\text{Daily mass flow of Tanfloc} = 10\,\tfrac{mg}{L}\cdot 3600\,\tfrac{m^3}{day}\cdot 1000\,\tfrac{L}{m^3}\cdot\tfrac{kg}{10^6 mg} = 36\,\tfrac{kg}{day}$$

Equation 3-6: Calculation of daily mass flow for the $FeCl_3$+Tanfloc combination

Multiplying by the cost per kg:

$$\text{Daily cost of } FeCl_3 = 108\,\frac{\text{kg}}{\text{day}}\cdot 0.3\,\frac{\text{USD}}{\text{kg}} = 32\,\frac{\text{USD}}{\text{day}}$$
$$\text{Daily cost of Tanfloc} = 36\,\frac{\text{kg}}{\text{day}}\cdot 0.93\,\frac{\text{USD}}{\text{kg}} = 33\,\frac{\text{USD}}{\text{day}}$$

Equation 3-7: Calculation of daily operational costs for the $FeCl_3$+Tanfloc combination

The total daily cost of the $FeCl_3$+Tanfloc option is thus 65 USD. Following the same reasoning, the cost of using Tanfloc alone is:

$$\text{Daily mass flow of Tanfloc} = 30\,\frac{\text{mg}}{\text{L}}\cdot 3600\,\frac{\text{m}^3}{\text{day}}\cdot 1000\,\frac{\text{L}}{\text{m}^3}\cdot\frac{\text{kg}}{10^6\text{mg}} = 108\,\frac{\text{kg}}{\text{day}}$$
$$\text{Daily cost of Tanfloc} = 108\,\frac{\text{kg}}{\text{day}}\cdot 0.93\,\frac{\text{USD}}{\text{kg}} = 116\,\frac{\text{USD}}{\text{day}}$$

Equation 3-8: Calculation of daily mass flow and cost for Tanfloc

As estimated above, the proposed CEPT plant will cost 60,000 USD, of which approximately 1200 USD can be allocated for chemical dosing tanks, piping and pumps. For the Tanfloc option, this value decreases to approximately 700 USD, which does not represent a significant difference. It can be concluded that capital costs of equipment are comparable for both options, since the fixed costs of all the rest of the equipment are much greater. Furthermore, operation and maintenance costs such as labor and parts were not factored into the cash flow estimate, as they will also be comparable for both options.

Using a discount rate of 10%, typical value for this type of project, and a project life of 10 years, the net present value of the cost of the $FeCl_3$+Tanfloc option is approximately 215,000 USD, while that of Tanfloc alone is approximately 320,000 USD. This points to $FeCl_3$+Tanfloc as the best option for treatment, in terms of cost.

With respect to ease of operation, using only one chemical is more efficient as it requires less maintenance. However, the cost efficiency of using two chemicals, $FeCl_3$ as coagulant and Tanfloc as flocculant, is much higher and relevant in this case, thus will constitute the best option for treatment in this case. One major objective of this proposed plant is to be cost-effective for a developing country, thus further supporting the decision to use $FeCl_3$+Tanfloc. Furthermore, this option offers the highest versatility, since having two chemicals with which to adjust the treatment makes it easier to regulate its effectiveness and control operational costs.

3.6.6 Analysis of relevant regulations

According to Brazilian regulation nº 010/86, issued by the Environmental Policy Commission on September 8, 1980, treated wastewater that is to be discharged into natural bodies of water should meet, among others, the following specifications:

Table 3-6: Summary of relevant regulation requirements for treated wastewater discharge

Parameter	**Value**
PH	6.5 to 8.5 (±0.5)
COD	90 mg/L max.
BOD_5	60 mg/L max. (or 85% removal)
TSS	100 mg/L max.
Phosphorus	0.1 mg/L max.
Fecal coliforms	1000 per 100 mL max.

The level of pH required will be achieved through CEPT, as will the TSS requirement. Disinfection with NaClO will effectively kill most pathogens in the effluent, complying with this portion of the regulatory requirements. However, phosphorus levels after CEPT will remain above regulation standards, as will COD levels. Using the average raw wastewater characteristics presented in section 3.4 (page 36), the corresponding removal rates discussed above and the correlation between COD and BOD established in section 3.3.3 (page 33), the expected levels of BOD for each treatment option are:

Table 3-7: Expected BOD for treated water

Treatment Option	**Wastewater COD**	**Wastewater BOD**	**Removal of COD & BOD**	**Expected Treated Water COD**	**Expected Treated Water BOD**
$FeCl_3$ + Tanfloc	494	296	54 %	227	136
Tanfloc	494	296	64 %	178	107

An increase in dosing can achieve removal rates that will allow the effluent to reach regulation standards, but since removal rates of BOD for CEPT usually do not exceed 70%, unless the incoming wastewater's BOD remains below 200 mg/L, this will not ensure that the effluent will meet the standard. To meet the regulation in full, later use of secondary treatment will be necessary. Having applied CEPT, this treatment will be less costly than having implemented conventional primary treatment. Stabilization ponds or lagoons are strongly recommended for their ease of operation.

4. CEPT Plant Design

4.1 Process description

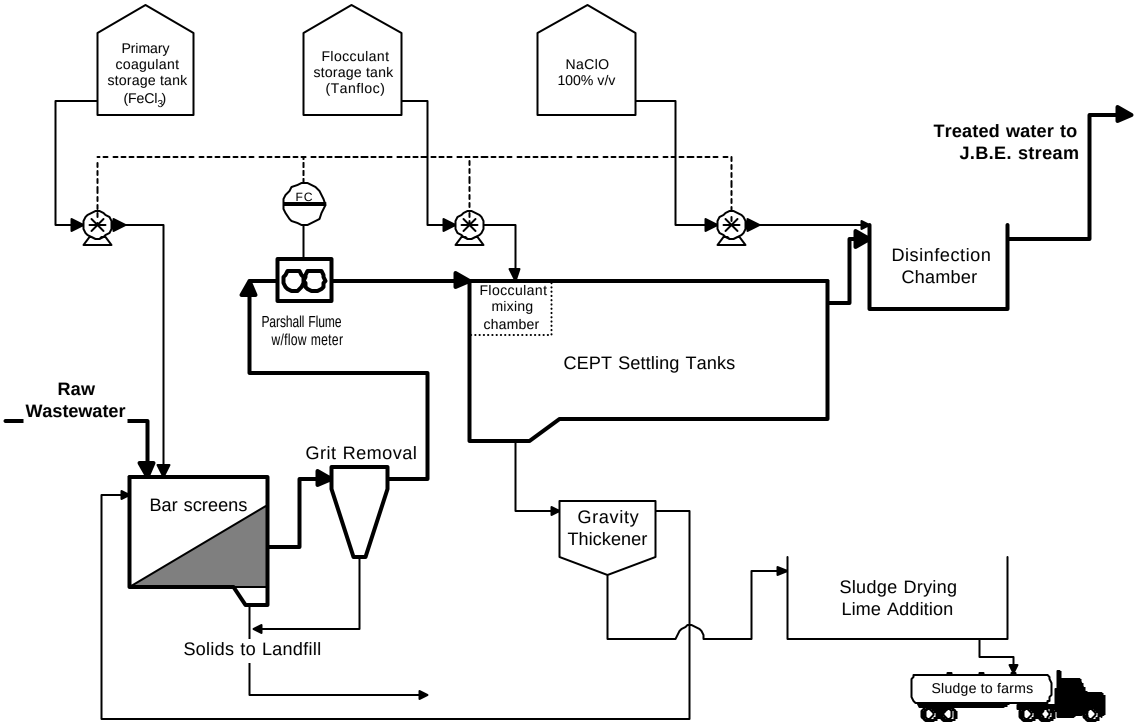


Figure 4-1: Process Flow Diagram (with Instrumentation)

Raw wastewater, collected through the sewer system, arrives at the plant and flows first through bar screens, where coarse solids, such as rags, twigs and rocks, are separated from the stream. At this point, the coagulant is injected, the dosing for which will be determined by a feedback control system tied into the flow meter located in the Parshall flume (downstream). Injection of coagulant at this point will ensure proper and full mixing.

Next, the water flows through the grit removal chamber, where finer solids, such as sand, are separated. The stream then flows through a Parshall flume, where volumetric flow is constantly measured and used to control the dosing of coagulant.

The flocculant is injected at this point, just before the water enters the CEPT settling tanks. Water then flows through the CEPT tank to let solids settle out of it. Finally, water passes through the disinfection contact chamber, where NaClO in liquid solution is mixed with the water, the dosing of which is also controlled by the flow meter in the Parshall flume. As an option, the dosing of the disinfectant could be controlled by an online chlorine analyzer. Finally, the treated water is discharged into the Jardim de Boa Esperança stream.

Sludge is taken from the bottom of the CEPT tank into a gravity thickener, and the thickened sludge flows into the sludge drying beds, where lime is added for disinfection and the sludge is left to dry (Stout, 2002).

4.2 Dimensioning of CEPT settling tank

This CEPT plant will serve a population of 20,000 inhabitants that discharge their wastewater into the Jardim de Boa Esperança stream. Based on the typical flow rates of wastewater for Latin American countries (Metcalf & Eddy, 1991), it will be assumed that each inhabitant will produce 180 liters of wastewater per day. Therefore, the incoming flow of wastewater will be:

$$\text{Incoming Flowrate} = \frac{20{,}000 \text{ inhab.} \times 180 \text{ liters / inhab.}}{1000 \text{ liters } / \text{m}^3} = 3600 \text{ m}^3\text{/day}$$

Equation 4-1: Calculation of incoming wastewater flow rate

Operating overflow rate will be set at 60 m/day a typical value for CEPT (Morrisey and Harleman, 1992), which also provided adequate COD, TSS and turbidity removal rates during jar testing. Thus, the required footprint (area) for the CEPT tank will be:

$$\text{Footprint (Area)} = \frac{3600 \text{ m}^3\text{/day}}{60 \text{ m/day}} = 60 \text{ m}^2$$

Equation 4-2: Calculation of footprint for CEPT tank

Tank depth will be set at 3 m, which is a typical value for CEPT tanks, and it takes into account the difficulty of building deeper tanks. Thus, the tank volume will be:

$$\text{Volume} = 60 \text{ m}^2 \times 3 \text{ m} = 180 \text{ m}^3$$

Equation 4-3: Calculation of CEPT tank volume

Tank dimensions for CEPT are typically such that the tank has a rectangular shape, to allow space for longitudinal mixing and proper settling. For this reason, a width of 3 m is set. Thus, the total required length of the CEPT tank would be:

$$\text{Length} = \frac{180\ \text{m}^3}{3\ \text{m} \times 3\ \text{m}} = 20\ \text{m}$$

Equation 4-4: Calculation of CEPT tank length

For construction, this length will be separated into two 10 m long tanks, with approximately three additional meters for inlet and outlet space in each tank. The first tank will also have a baffle 4 meters after the inlet to allow for flocculant mixing. The residence time in the CEPT tanks will be:

$$\text{Residence Time} = \frac{180\ \text{m}^3}{3600\ \text{m}^3/\text{day}} \times 24\ \tfrac{\text{hours}}{\text{day}} = 1.2\ \text{hours}$$

Equation 4-5: Calculation of CEPT tank residence time

This residence time fits within the suggested standard for CEPT settling tanks (Metcalf & Eddy, 1991), thus confirming the choice of assumed parameters. Although typical values are closer to one hour, the 20% of excess residence time will be used to buffer peak flows.

4.3 Dimensioning of disinfection chamber

To achieve the desired disinfection, which will yield an effluent with 1000 or less fecal coliforms per 100 mL, as required by Brazilian regulations (see page 52), contact time with NaClO will be 30 minutes and under peak conditions, contact time can lower to 20 minutes while maintaining disinfection requirements (ASCE, 1998, page 14-106). A plug flow is preferred for disinfection, in order to enable extensive and intimate contact between the disinfectant and the water. For a volumetric flow of 3600 m^3/day, the required volume for the disinfection chamber is:

$$\mathrm{Vol} = 3600\,\frac{\mathrm{m}^3}{\mathrm{day}} \cdot 30\,\mathrm{min} \cdot \frac{\mathrm{day}}{1440\,\mathrm{min}} = 75\mathrm{m}^3$$

Equation 4-6: Calculation of disinfection chamber volume

Maintaining the geometry of 3 m deep and 3 m wide used for the CEPT tank, the disinfection chamber requires a total length of:

$$\mathrm{Length} = \frac{75\,\mathrm{m}^3}{3\,\mathrm{m} \times 3\,\mathrm{m}} = 8.3\,\mathrm{m}$$

Equation 4-7: Calculation of disinfection chamber length

4.4 Plant location and layout

The map below (Figure 4-2) shows the area where the first CEPT plant will be built at the Jardim de Boa Esperança stream. For the plant layout, a simple process-oriented distribution will be proposed. Figure 4-3 depicts the proposed layout.

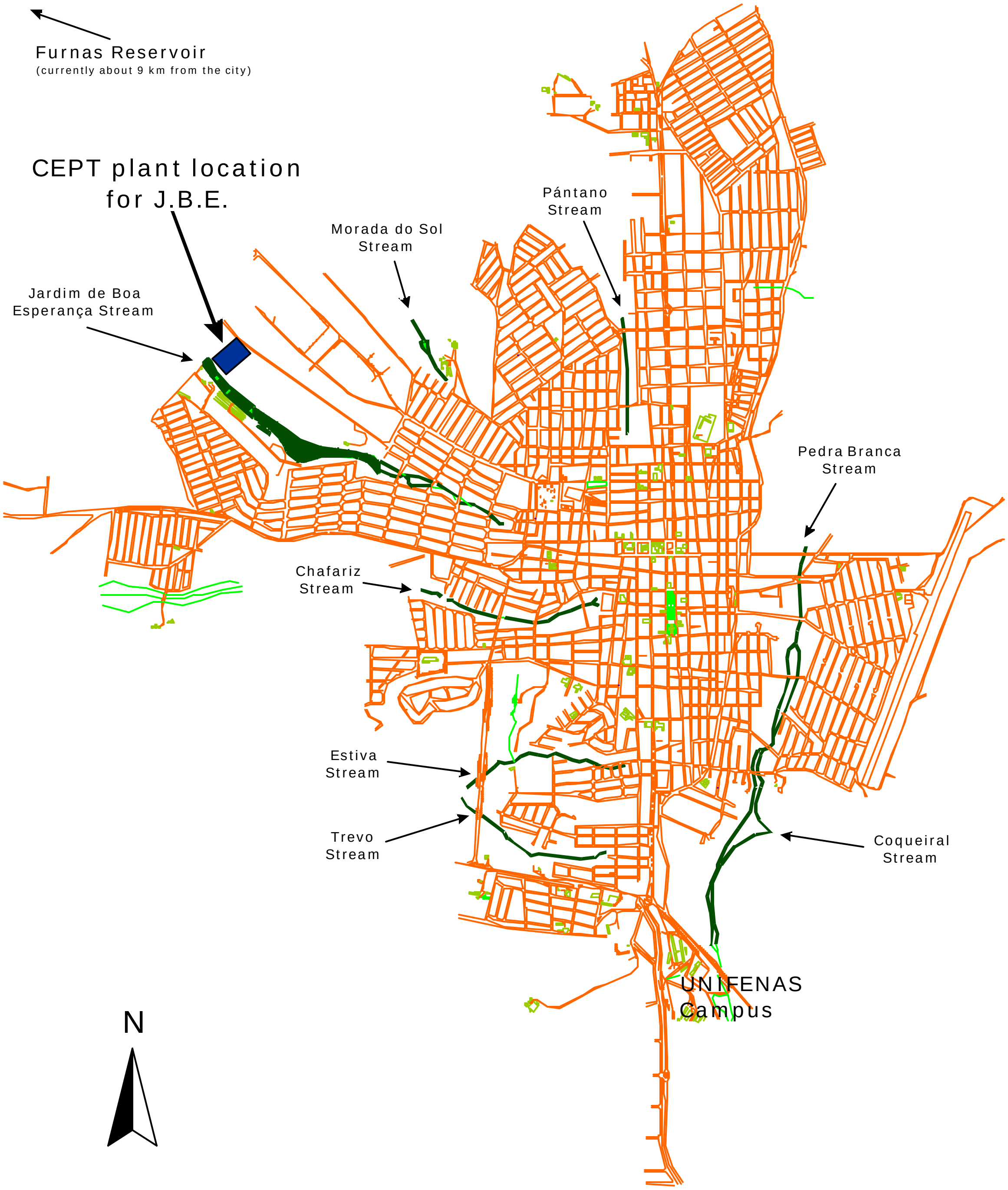


Figure 4-2: CEPT plant location for the Jardim de Boa Esperança stream (Source: Alfenas City Hall, Office of Cartography)

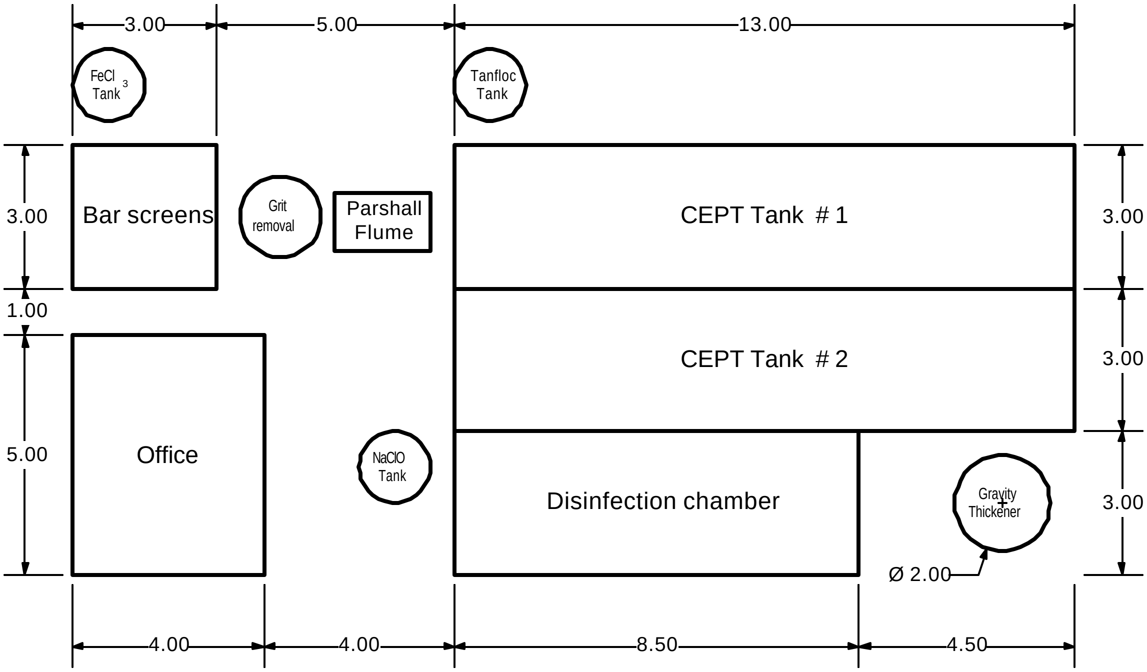


Figure 4-3: Proposed plant layout, distances in meters

5. Equipment specifications

5.1 Bar screens and grit chamber

To remove coarse solids that usually flow together with wastewaters, two unit operations of pre-treatment will be used: bar screens and grit removal.

Bar screens will be 3 meters wide and comprised of sixty 10 mm wide by 30 mm deep stainless steel bars, with a spacing of 40 mm between them and a slope of 45º. The method for cleaning will be manual.

For grit removal, a vortex-type grit chamber will be used (Metcalf & Eddy, 1991). The detention time in the grit chamber will be 30 seconds. Diameter will be set at 1.2 m, and height will be 1.5 m for the cylindrical portion of the chamber; the conical bottom will have a total height of 35 cm.

5.2 Parshall flume with flow meter

A vinyl pre-fabricated Parshall flume will be used to measure the incoming flow of raw wastewater. A magnetic flow meter will be included to provide volumetric flow data for the control system. A four-way programmable logic controller (PLC) will gather the signal from the Parshall flume and emit signals to control the flow of the three dosing pumps.

5.3 Chemical storage tanks and dosing system

Roofed PVC tanks will be used to store a stock of 8 days of both CEPT chemicals and disinfectant. Diaphragm pumps will be used to dose these into the proper section of the process.

For $FeCl_3$, the required volume to store 8 days will be:

$$\begin{aligned}&\text{Daily FeCl}_3\text{ consumed} = 30\,\tfrac{\text{mg}}{\text{L}} \times 3600\,\tfrac{\text{m}^3}{\text{day}} \times 1000\,\tfrac{\text{L}}{\text{m}^3} \times 10^{-6}\,\tfrac{\text{kg}}{\text{mg}} = 108\,\tfrac{\text{kg}}{\text{day}} \\ &\delta_{\text{FeCl}_3\text{ aqueous solution}} \approx 1\tfrac{\text{g}}{\text{mL}} \Rightarrow 108\,\tfrac{\text{kg}}{\text{day}} \times 8\text{ days} = 864\text{ kg} \approx 864\text{ L}\end{aligned}$$

Equation 5-1: Calculation of $FeCl_3$ storage tank

To ensure proper storage capacity, the $FeCl_3$ tank will be specified at 1000 L, to allow for unexpected problems with supply.

For Tanfloc and NaClO, the required volume to store 8 days will be:

$$\begin{aligned}&\text{Daily Tanfloc or NaClO consumed} = 10\,\tfrac{\text{mg}}{\text{L}} \times 3600\,\tfrac{\text{m}^3}{\text{day}} \times 1000\,\tfrac{\text{L}}{\text{m}^3} \times 10^{-6}\,\tfrac{\text{kg}}{\text{mg}} = 36\,\tfrac{\text{kg}}{\text{day}} \\ &\delta_{\text{Tanfloc or NaClO aqueous solution}} \approx 1\tfrac{\text{g}}{\text{mL}} \Rightarrow 36\,\tfrac{\text{kg}}{\text{day}} \times 8\text{ days} = 288\text{ kg} \approx 288\text{ L}\end{aligned}$$

Equation 5-2: Calculation of Tanfloc and NaClO storage tanks

To ensure proper storage capacity, the Tanfloc tank will be specified at 350 L, to allow for unexpected problems with supply. Following this same reasoning, the NaClO storage tank should also have this volume, as its consumption is the same.

5.4 CEPT settling tanks and scraper system

Concrete tanks will be used, with the typical sump at the head of the tank, which will allow sludge collection. The tanks will be connected by a 30 cm wide weir, which will allow water to flow from one to the next.

Continuous moving sludge and scum scrapers will be used, which will assist in gathering the sludge as it settles and in removing lipids and other scum from the surface of the water. An option in this case would be to construct this mechanism using locally available technology, but it could also be imported directly from a manufacturer, for instance Finnchain (http://www.finnchain.fi)

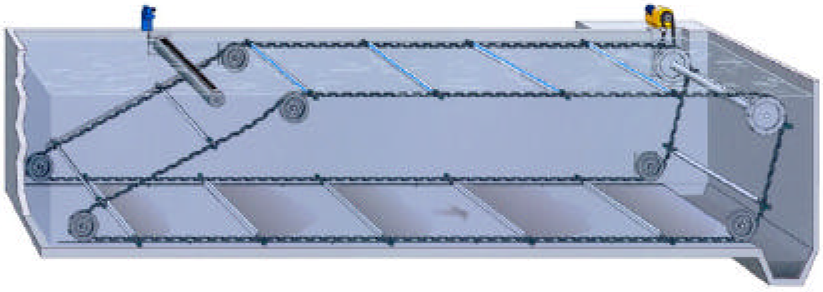


Figure 5-1: Illustration of a sludge and scum scraper (Source: Finnchain, http://www.finnchain.fi)

5.5 Disinfection chamber

Concrete will also be used for the disinfection chamber. Two longitudinal baffles will be added, 1 meter apart, to promote plug flow.

6. Conclusions

The best first step to solve the public health, environmental and wastewater management problems of the Furnas region is to install CEPT plants throughout its extension. This will initially inhibit further deterioration of this very valuable body of water and allow it to recover its former quality. A second stage will be to install secondary treatment for the wastewater, maximizing the quality of the effluents discharged into the lake.

For the Jardim da Boa Esperança stream, a treatment dosage of 30 mg/L of $FeCl_3$ and 10 mg/L of Tanfloc was found to yield the best results. This treatment will comply with bacteriological regulations and other key parameters, while remaining a cost-effective solution.

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Appendix A – Field data: jar testing results

Below are presented the results of all jar testing and laboratory analysis data obtained during the field study. In all cases, the raw wastewater used for the jar test is typified by the date and time it was collected, together with its Turbidity (NTU), Total suspended solids (mg/L), Chemical Oxygen Demand (mg/L) phosphorus (mg/L) and pH. Then, each jar test is typified by the type and dosing of coagulant and flocculant that were used and the overflow rates sampled. Each sample of treated water is typified by the values obtained for Turbidity, TSS, COD and phosphorus.

Date/Time:	Raw wastewater characteristics				
Jan 9, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
10:00 am	**230**	**n/a**	**387**	**n/a**	**10**

Coagulant	Coag. Dose (ppm)	Flocculant	Floc. Dose (ppm)	SOR (m/day)	Turb. (NTU)	TSS (mg/L)	COD (mg/L)	Phos. (mg/L)
Alum	15			60	175	50	286	
Alum	20			60	115	180	262	
Alum	25			60	108			
Alum	30			60	106	100	296	
Alum	40			60	99.7			
No chemicals				60	148	50	256	
Alum	15			8.64	74.8			
Alum	20			8.64	121			
Alum	25			8.64	68.6			
Alum	30			8.64	50.8			
Alum	40			8.64	52.7			
No chemicals				8.64	105			

Date/Time:	Raw wastewater characteristics				
Jan 9, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
11:30 am	**173**	**n/a**	**659**	**n/a**	**10**

Coagulant	**Coag. Dose (ppm)**	**Flocculant**	**Floc. Dose (ppm)**	**SOR (m/day)**	**Turb. (NTU)**	**TSS (mg/L)**	**COD (mg/L)**	**Phos. (mg/L)**
$FeCl_3$	10			60	140			
$FeCl_3$	15			60	120	120	439	
$FeCl_3$	20			60	77.5	120	316	
$FeCl_3$	25			60	86			
$FeCl_3$	30			60	47	50	308	
No chemicals				60	160	170	515	
$FeCl_3$	10			8.64	77.5			
$FeCl_3$	15			8.64	54.1			
$FeCl_3$	20			8.64	57.7			
$FeCl_3$	25			8.64	50.2			
$FeCl_3$	30			8.64	34.1			
No chemicals				8.64	88.9			

Date/Time:	Raw wastewater characteristics				
Jan 9, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
11:30 am	**173**	**n/a**	**659**	**n/a**	**10**

Coagulant	**Coag. Dose (ppm)**	**Flocculant**	**Floc. Dose (ppm)**	**SOR (m/day)**	**Turb. (NTU)**	**TSS (mg/L)**	**COD (mg/L)**	**Phos. (mg/L)**
Tanfloc	10			60	84.5	130	365	
Tanfloc	20			60	44.2	120	320	
Tanfloc	30			60	54.2	160	344	
Tanfloc	50			60	16.2			
Tanfloc	70			60	13.7			
No chemicals				60	119	100	553	
Tanfloc	10			8.64	44			
Tanfloc	20			8.64	35.9			
Tanfloc	30			8.64	22.8			
Tanfloc	50			8.64	8.46			
Tanfloc	70			8.64	6			
No chemicals				8.64	55.9			

Date/Time:	Raw wastewater characteristics				
Jan 10, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
10:00 am	**279**	**320**	**n/a**	**n/a**	**9**

Coagulant	Coag. Dose (ppm)	Flocculant	Floc. Dose (ppm)	SOR (m/day)	Turb. (NTU)	TSS (mg/L)	COD (mg/L)	Phos. (mg/L)
Tanfloc	10			60	165	120		6
Tanfloc	15			60	151	220		5
Tanfloc	20			60	144	220		4
Tanfloc	25			60	128	190		2.5
Tanfloc	30			60	117	160		1.5
No chemicals				60	182	220		5
Tanfloc	10			30	105	120		4
Tanfloc	15			30	98.7	50		1.5
Tanfloc	20			30	80.2	40		1.5
Tanfloc	25			30	82	100		2
Tanfloc	30			30	54.3	10		1.5
No chemicals				30	121	170		4

Date/Time:	Raw wastewater characteristics				
Jan 10, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
10:00 am	**279**	**320**	**n/a**	**n/a**	**9**

Coagulant	Coag. Dose (ppm)	Flocculant	Floc. Dose (ppm)	SOR (m/day)	Turb. (NTU)	TSS (mg/L)	COD (mg/L)	Phos. (mg/L)
Neutral polymer	0.1			60	174	200		5
Neutral polymer	0.5			60	125	170		2
Neutral polymer	1			60	116	110		2
Neutral polymer	2			60	74.6	70		1.5
Neutral polymer	5			60	75	67		1.5
No chemicals				60	164	140		4
Neutral polymer	0.1			30	75.1	730		2
Neutral polymer	0.5			30	63.5	80		1.5
Neutral polymer	1			30	70	49		1.5
Neutral polymer	2			30	56.2	46		1.5
Neutral polymer	5			30	60.2	42		1.5
No chemicals				30	96.1	85		2.5

Date/Time:	Raw wastewater characteristics				
Jan 11, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
9:00 am	**173**	**n/a**	**n/a**	**7.1**	**n/a**

Coagulant	**Coag. Dose (ppm)**	**Flocculant**	**Floc. Dose (ppm)**	**SOR (m/day)**	**Turb. (NTU)**	**TSS (mg/L)**	**COD (mg/L)**	**Phos. (mg/L)**
Alum	25	Tanfloc	25	60	18.7			
Alum	25	Anionic #20	0.5	60	97.5			
Alum	25	Anionic #5	0.5	60	28.1			
Alum	25	Cationic #14	0.5	60	48.6			
Alum	25	Cationic #36	0.5	60	35.3			
No chemicals				60	125			
Alum	25	Tanfloc	25	30	9			
Alum	25	Anionic #20	0.5	30	32.5			
Alum	25	Anionic #5	0.5	30	25			
Alum	25	Cationic #14	0.5	30	18.1			
Alum	25	Cationic #36	0.5	30	17.8			
No chemicals				30	48.2			

Date/Time:	Raw wastewater characteristics				
Jan 11, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
9:00 am	**173**	**n/a**	**n/a**	**7.1**	**n/a**

Coagulant	**Coag. Dose (ppm)**	**Flocculant**	**Floc. Dose (ppm)**	**SOR (m/day)**	**Turb. (NTU)**	**TSS (mg/L)**	**COD (mg/L)**	**Phos. (mg/L)**
$FeCl_3$	30	Anionic #20	0.5	60	8.32			
$FeCl_3$	30	Anionic #5	0.5	60	4.51			
$FeCl_3$	30	Cationic #36	0.5	60	6.67			
Alum	25	Anionic #20	0.5	60	80			
Alum	25	Anionic #5	0.5	60	8.95			
Alum	25	Cationic #36	0.5	60	35.3			
$FeCl_3$	30	Anionic #20	0.5	30	4.37			
$FeCl_3$	30	Anionic #5	0.5	30	4.42			
$FeCl_3$	30	Cationic #36	0.5	30	3.53			
Alum	25	Anionic #20	0.5	30	14			
Alum	25	Anionic #5	0.5	30	8.33			
Alum	25	Cationic #36	0.5	30	34.1			

Date/Time:	Raw wastewater characteristics				
Jan 11, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
9:00 am	**173**	**n/a**	**n/a**	**7.1**	**n/a**

Coagulant	Coag. Dose (ppm)	Flocculant	Floc. Dose (ppm)	SOR (m/day)	Turb. (NTU)	TSS (mg/L)	COD (mg/L)	Phos. (mg/L)
$FeCl_3$	12	Anionic #20	0.5	60	39.9	54		
$FeCl_3$	12	Anionic #5	0.5	60	17.6	103		
$FeCl_3$	12	Cationic #36	0.5	60	29	5		
Alum	15	Anionic #20	0.5	60	108	97		
Alum	15	Anionic #5	0.5	60	72.5	25		
Alum	15	Cationic #36	0.5	60	84	68		
$FeCl_3$	12	Anionic #20	0.5	30	16.7	73		
$FeCl_3$	12	Anionic #5	0.5	30	14.4	24		
$FeCl_3$	12	Cationic #36	0.5	30	13.3	17		
Alum	15	Anionic #20	0.5	30	78.3	69		
Alum	15	Anionic #5	0.5	30	55.7	34		
Alum	15	Cationic #36	0.5	30	50.4	23		

Date/Time:	Raw wastewater characteristics				
Jan 14, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
9:00 am	**162**	**142**	**409**	**6.9**	**10**

Coagulant	Coag. Dose (ppm)	Flocculant	Floc. Dose (ppm)	SOR (m/day)	Turb. (NTU)	TSS (mg/L)	COD (mg/L)	Phos. (mg/L)
Alum	20			60	152		413	
$FeCl_3$	15			60	60.9		288	
$FeCl_3$	10			60	76.4		303	
Tanfloc	15			60	98.9		326	
Tanfloc	10			60	111		331	
No chemicals				60	120		368	
Alum	20			30	55.9		299	
$FeCl_3$	15			30	52.7		273	
$FeCl_3$	10			30	60.5		270	
Tanfloc	15			30	75.3		289	
Tanfloc	10			30	77.9		298	
No chemicals				30	106		290	

Date/Time:	Raw wastewater characteristics				
Jan 14, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
9:00 am	**151**	**147**	**396**	**7.1**	**5.5**

Coagulant	Coag. Dose (ppm)	Flocculant	Floc. Dose (ppm)	SOR (m/day)	Turb. (NTU)	TSS (mg/L)	COD (mg/L)	Phos. (mg/L)
Alum	20			30	91.5	115	340	
Alum	15	Tanfloc	5	30	34.6	0	257	
$FeCl_3$	15			30	25.4	35	242	
Tanfloc	15			30	44.4	25	270	
Tanfloc	20			30	29.8	80	256	
No chemicals				30	60.6	25	275	

Date/Time:	Raw wastewater characteristics				
Jan 14, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
9:00 am	**156**	**172**	**362**	**7.2**	**6**

Coagulant	Coag. Dose (ppm)	Flocculant	Floc. Dose (ppm)	SOR (m/day)	Turb. (NTU)	TSS (mg/L)	COD (mg/L)	Phos. (mg/L)
Alum	20			30	50.8	35	268	
$FeCl_3$	20			30	18.4	15	222	
$FeCl_3$	30			30	16.1	-5	230	
Tanfloc	20			30	21.1	10	229	
Tanfloc	30			30	9.02	15	219	
No chemicals				30	49.9	30	255	

Date/Time:	Raw wastewater characteristics				
Jan 15, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
10:00 am	**168**	**227**	**575**	**6.9**	**4.5**

Coagulant	Coag. Dose (ppm)	Flocculant	Floc. Dose (ppm)	SOR (m/day)	Turb. (NTU)	TSS (mg/L)	COD (mg/L)	Phos. (mg/L)
Alum	30	Tanfloc	10	30	84.6	0	329	
Alum	25	Tanfloc	10	30	87	118	329	
FeCl$_3$	30	Tanfloc	10	30	36.3	0	246	
FeCl$_3$	25	Tanfloc	10	30	39.2	57	239	
Tanfloc	35			30	27.4	48	233	
No chemicals				30	99.1	109	346	

Date/Time:	Raw wastewater characteristics				
Jan 15, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
10:00 am	**255**	**263**	**606**	**7.0**	**4.5**

Coagulant	Coag. Dose (ppm)	Flocculant	Floc. Dose (ppm)	SOR (m/day)	Turb. (NTU)	TSS (mg/L)	COD (mg/L)	Phos. (mg/L)
FeCl3	20	Tanfloc	10	17.28	53.5	95	201	
FeCl3	25	Tanfloc	10	17.28	40.75	70	190	
FeCl3	25	Tanfloc	5	17.28	47.35	40	187	
Tanfloc	30			17.28	37.8	25	187	
Tanfloc	35			17.28	37	10	191	
No chemicals				17.28	101	109	232	

Date/Time:	Raw wastewater characteristics				
Jan 16, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
9:00 am	**209**	**113**	**269**	**6.8**	**n/a**

Coagulant	**Coag. Dose (ppm)**	**Flocculant**	**Floc. Dose (ppm)**	**SOR (m/day)**	**Turb. (NTU)**	**TSS (mg/L)**	**COD (mg/L)**	**Phos. (mg/L)**
FeCl$_3$	25	Tanfloc	5	30	88.1	33	146	
FeCl$_3$	25	Tanfloc	5	17.28	84.6	17	139	
FeCl$_3$	30	Tanfloc	5	30	78.9	35	138	
FeCl$_3$	30	Tanfloc	5	17.28	80.3	23	133	
FeCl$_3$	30	Tanfloc	2	30	73.7	20	141	
FeCl$_3$	30	Tanfloc	2	17.28	72.9	25	141	
Tanfloc	20			30	86.4	38	145	
Tanfloc	20			17.28	89.6	35	141	
Tanfloc	30			30	85	17	139	
Tanfloc	30			17.28	85.2	27	124	
No chemicals				30	174	62	175	
No chemicals				17.28	154	48	147	

Date/Time:	Raw wastewater characteristics				
Jan 16, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
9:00 am	**192**	**n/a**	**282**	**6.9**	**n/a**

Coagulant	**Coag. Dose (ppm)**	**Flocculant**	**Floc. Dose (ppm)**	**SOR (m/day)**	**Turb. (NTU)**	**TSS (mg/L)**	**COD (mg/L)**	**Phos. (mg/L)**
FeCl$_3$	25	Tanfloc	5	60	48.6	33	138	
FeCl$_3$	25	Tanfloc	5	30	29.3	10	125	
Tanfloc	30			60	31.8	22	131	
Tanfloc	30			30	23.4	3	137	
				60	138	75	191	
				30	93.6	45	145	

Date/Time:	Raw wastewater characteristics				
Jan 17, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
10:00 am	**169**	**176**	**448**	**6.7**	**n/a**

Coagulant	**Coag. Dose (ppm)**	**Flocculant**	**Floc. Dose (ppm)**	**SOR (m/day)**	**Turb. (NTU)**	**TSS (mg/L)**	**COD (mg/L)**	**Phos. (mg/L)**
$FeCl_3$	25	Tanfloc	5	30	72.5	45	191	
$FeCl_3$	30	Tanfloc	5	30	79.5	55	183	
$FeCl_3$	30	Tanfloc	10	30	54.8	38	159	
$FeCl_3$	40	Tanfloc	5	30	68.7	55	189	
$FeCl_3$	40	Tanfloc	10	30	55.7	48	190	
No chemicals				30	154	117	281	

Date/Time:	Raw wastewater characteristics				
Jan 17, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
10:00 am	**183**	**234**	**506**	**6.7**	**n/a**

Coagulant	**Coag. Dose (ppm)**	**Flocculant**	**Floc. Dose (ppm)**	**SOR (m/day)**	**Turb. (NTU)**	**TSS (mg/L)**	**COD (mg/L)**	**Phos. (mg/L)**
Alum	50	Tanfloc	10	30	71.6	43	219	
Tanfloc	40			30	40.7	30	143	
$FeCl_3$	30	Tanfloc	5	30	54.2	73	152	
$FeCl_3$	30	Tanfloc	10	30	56.9	17	158	
$FeCl_3$	30	Tanfloc	15	30	50.9	40	141	
No chemicals				30	122	85	217	

Date/Time:	Raw wastewater characteristics				
Jan 18, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
9:00 am	**171**	**255**	**537**	**6.6**	**n/a**

Coagulant	**Coag. Dose (ppm)**	**Flocculant**	**Floc. Dose (ppm)**	**SOR (m/day)**	**Turb. (NTU)**	**TSS (mg/L)**	**COD (mg/L)**	**Phos. (mg/L)**
$FeCl_3$	30	Tanfloc	10	60	80.3	88	235	
$FeCl_3$	30	Tanfloc	10	30	92.7	77	224	
Tanfloc	40			60	81.4	40	226	
Tanfloc	40			30	67.1	48	198	
$FeCl_3$	30	Tanfloc	5	60	93.3	86	222	
No chemicals				60			347	
$FeCl_3$	30	Tanfloc	10	60 (*)	82	105	224	
$FeCl_3$	30	Tanfloc	10	30 (*)	92.7		206	
Tanfloc	40			60 (*)	79.5	48	200	
Tanfloc	40			30 (*)	72.3		188	
$FeCl_3$	30	Tanfloc	5	60 (*)	96.9		225	
No chemicals				60 (*)	137	157	338	

(*) Disinfected with 0.01 ppm of NaClO

Date/Time:	Raw wastewater characteristics				
Jan 18, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
2:00 pm	**166**	**248**	**604**	**6.5**	**n/a**

Coagulant	**Coag. Dose (ppm)**	**Flocculant**	**Floc. Dose (ppm)**	**SOR (m/day)**	**Turb. (NTU)**	**TSS (mg/L)**	**COD (mg/L)**	**Phos. (mg/L)**
FeCl3	30	Tanfloc	10	60	71.3	88	174	
FeCl3	30	Tanfloc	10	43.2	67.3	69	149	
FeCl3	30	Tanfloc	10	34.56	62.3	63	146	
FeCl3	30	Tanfloc	10	30	74.2	73	158	
FeCl3	30	Tanfloc	10	24.68	67.1	53	181	
No chemicals				60	173	183	414	
FeCl3	30	Tanfloc	10	60 (*)	71.6	85	189	
FeCl3	30	Tanfloc	10	43.2 (*)	64.7	0	203	
FeCl3	30	Tanfloc	10	34.56 (*)	56.6	0	150	
FeCl3	30	Tanfloc	10	30 (*)	69.4	75	173	
FeCl3	30	Tanfloc	10	24.68 (*)	58	0	144	
No chemicals				60 (*)	163	213	389	

(*) Disinfected with 0.1 ppm of NaClO

Date/Time:	Raw wastewater characteristics				
Jan 21, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
9:00 am	**239**	**437**	**980**	**6.7**	**n/a**

Coagulant	**Coag. Dose (ppm)**	**Flocculant**	**Floc. Dose (ppm)**	**SOR (m/day)**	**Turb. (NTU)**	**TSS (mg/L)**	**COD (mg/L)**	**Phos. (mg/L)**
$FeCl_3$	30	Tanfloc	10	60	178	203	570	
$FeCl_3$	30	Tanfloc	10	43.2	128	163	436	
$FeCl_3$	30	Tanfloc	10	30	110	107	396	
Tanfloc	40			60	113	160	490	
Tanfloc	35			60	126	180	479	
No chemicals				60	255	415	806	
$FeCl_3$	30	Tanfloc	10	60 (*)	132	263	434	
$FeCl_3$	30	Tanfloc	10	43.2 (*)	107	150	456	
$FeCl_3$	30	Tanfloc	10	30 (*)	79.7	100	648	
Tanfloc	40			60 (*)	101	153	443	
Tanfloc	35			60 (*)	117	170	407	
No chemicals				60 (*)	253	420	679	

(*) Disinfected with 10 ppm of NaClO

Date/Time:	Raw wastewater characteristics				
Jan 22, 2002	Turbidity (NTU)	TSS (mg/L)	COD (mg/L)	pH	Phosphorus (mg/L)
8:00 am	**n/a**	**117**	**339**	**7.0**	**n/a**

Coagulant	**Coag. Dose (ppm)**	**Flocculant**	**Floc. Dose (ppm)**	**SOR (m/day)**	**Turb. (NTU)**	**TSS (mg/L)**	**COD (mg/L)**	**Phos. (mg/L)**
$FeCl_3$	30	Tanfloc	10	30			169	
$FeCl_3$	30	Tanfloc	10	17.28			183	
$FeCl_3$	30	Tanfloc	10	30			155	
$FeCl_3$	30	Tanfloc	10	15.7			142	
Tanfloc	35			30			168	
Tanfloc	35			17.28			154	
$FeCl_3$	30	Tanfloc	10	30 (*)		44	198	
$FeCl_3$	30	Tanfloc	10	17.28 (*)		46	183	
$FeCl_3$	30	Tanfloc	10	30 (*)		45	127	
$FeCl_3$	30	Tanfloc	10	15.7 (*)		33	123	
Tanfloc	35			30 (*)		16	165	
Tanfloc	35			17.28 (*)		19	143	

(*) Disinfected with 10 ppm of NaClO