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COMBINED PHYSICAL-CHEMICAL AND BIOLOGICAL TREATMENT OF MUNICIPAL WASTEWATER UNDER COLD WEATHER CONDITIONS

BY

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Abstract

Innovative Combined Physical-Chemical and Biological process system has been elaborated and proposed as an alternative technology for municipal wastewater treatment plants operation. In the series of laboratory bench-scale experiments typical raw municipal wastewater from the Town of Lee, Massachusetts was treated directly, or elevated to design concentrations (BOD5 / TSS / NH3-N = 250 mg/L / 250 mg/L / 25 mg/L) before treatment. The current and future National Pollutant Discharge Elimination System (NPDES) effluent limitations were the goals for wastewater treatment in this research. Innovative Dissolved Air Flotation (DAF) Technology was applied for primary and secondary clarification. Improved activated sludge single-sludge process was applied for biological treatment (carbonaceous oxidation, nitrification and denitrification) under simulated cold weather conditions. Three complex experiments were performed to prove the system efficiency. It is concluded that the combination of primary DAF, aerobic carbonaceous oxidation, aerobic nitrification, anoxic denitrification, secondary DAF-Filtration and chlorination is an effective innovative system for municipal wastewater treatment. The future NPDES effluent standards can be met. Addition of returned activated sludge (RAS) stabilization tank will increase the efficiency of biological treatment.
CHAPTER I

INTRODUCTION

At present time, in an era of urbanization, the municipal wastewater treatment processes became the objects of the special attention of the government and public. An increase in city population is creating additional demands for their sewage treatment facilities. Based on the United States Environment Protection Agency (USEPA) Needs Survey approximately one half of existing conventional municipal wastewater treatment plants (WWTP) needs some form of construction to achieve compliance with their final National Pollutant Discharge Elimination System (NPDES) discharge requirements [1]. High financial commitment will be required to improve the current situation by conventional technologies. Future economic challenges loom greater than other aspects of wastewater management beyond the treatment plant.

In consideration of regulatory requirements, public goals, financial constraints, introducing alternative innovative technologies into wastewater treatment plants for reliable and economical operation becomes an important task.

The experimental objectives within the framework of the presented paper are:

- To study and understand the needs for improvement of an existing municipal wastewater treatment systems;
- To develop new innovative approach for municipal wastewater purification by applying a combined physical-chemical-biological treatment process;
- To explore the possibility of using DAF as a primary clarifier for chemical treatment as well as clarification.
- To explore the possibility of using DAF-Filtration (DAFF) as a secondary clarifier.
- To develop a new biological wastewater treatment process involving the use of contact stabilization flow diagram, Single-Sludge concept for carbonaceous oxidation, nitrification and denitrification, DAF sludge harvesting, under cold weather conditions.
- To investigate the feasibility of using chlorination for ammonia removal.
CHAPTER II
BACKGROUND INFORMATION AND LITERATURE REVIEW

2.1. Conventional Municipal Wastewater Treatment Plant
    (Lee Wastewater Treatment Facilities)

Investigations were performed on the raw wastewaters from the Town of Lee, in Berkshire County, Massachusetts, USA.

The Lee (Wastewater Treatment Facilities) was originally designed and constructed in the late 1960’s to meet a design year 1981 projected service population of 8000 persons. The original design was for 1.0 MGD extended aeration activated sludge process. Design parameters and design criteria are presented below [2]:

**Population of Lee, Massachusetts:**
Historical Town’s population = 6,100 – 6,400;
Seasonal population = 2,000;
Peak population = 8,400.

**Historical design flows of Lee WWTF wastewater:**
Average design flow = 1.0-1.5 MGD;
Maximum day flow = 2.0-2.6 MGD;
Peak design flow = 2.5-3.75 MGD.

**Historical plant influent (raw sewage) of Lee WWTF:**
Influent BOD$_5$ = 130-157 mg/L (design BOD$_5$=250 mg/L);
Influent TSS = 80-133 mg/L (design TSS = 250 mg/L);
Influent pH = 5-9 units.

**NPDES effluent limits for Lee WWTF (until 2000 year)**
Effluent BOD$_5$ = 30 mg/L or below;
Effluent TSS = 30 mg/L;
Effluent NH$_3$-N limits = none required;
Effluent pH = 6.5-8.0 units.
Conventional municipal wastewater treatment system for small communities (on the example of Lee WWTF), generally, consists of the following components incorporating physical and biological processes (Figure 1):

1. Preliminary waste water treatment facilities: screen and grit chamber;
2. Primary clarification is optional and usually is not present in flow diagrams of conventional municipal wastes treatment systems, but it can be presented by sedimentation units with long detention time (∼1-2 hours); if advanced chemical treatment is involved in primary clarification the additional units (coagulation, flocculation basins) are required, which moderately increases the cost of WWTP and is not used in practice;
3. Secondary treatment is represented by biological processes: Activated Sludge or Trickling Filter, Rotating Biological Contractors, etc., plus secondary clarification.
4. Secondary clarification by sedimentation: detention time (∼2-4 hours), long time usually required and sequentially larger size of the unit to produce higher quality effluent;
5. Chlorine contact basin.

Using all these components Lee WWTF is not able to meet the final effluent standards required by NPDES in 1999 during the time of peak flow related to infiltration and seasonal population addition. In March 2000 the Commonwealth of Massachusetts established new EFFLUENT LIMITATIONS AND MONITORING REQUIREMENTS for upgrading of Lee WWTF:

\[
\begin{align*}
\text{BOD}_5 & < 20 \text{ mg/L}, \\
\text{TSS} & < 20 \text{ mg/L}, \\
\text{Total P} & < 0.7 \text{ mg/L}, \\
\text{NH}_3-N & < 10 \text{ mg/L}.
\end{align*}
\]

To execute this task an alternative Combined Physical-Chemical and Biological approach (Figure 2) to municipal wastewaters treatment has been proposed and studied.
Figure 1. Flow Diagram of a Conventional Municipal Wastewater Treatment Plant
Figure 2. Flow Diagram of Alternative Innovative Combined Physical-Chemical and Biological Process for Municipal Wastewater Treatment
2.2. Innovative Physical-Chemical and Biological Processes for Municipal Wastewater Treatment

Many clarification steps are used in the treatment of raw municipal wastewater. The general purification procedure of such wastes manifests itself a combination of both Physical-Chemical and Biological Treatment processes. This complex system is highly successful in terms of effective removal of the biodegradable pollutants from municipal wastewater, containing both particulates and dissolved solids.

However, the biological process is extremely sensitive to changes in hydraulic loading (infiltration, seasonal increasing of town population) and wastewater composition, which may lead to upset the biological treatment process. In this case, the entire wastewater flow has to be treated by physicochemical processes, which involve pre-treating the influent to the bio-reactor and further preventing insufficiently treated effluent discharge to a receiving water body.

Innovative approach for municipal waste waters treatment involves the following physical-chemical and biological processes (Figure 2):

1. Preliminary wastewater treatment facilities: coarse screen, grit chamber and fine screening;
2. Primary clarification by Dissolved Air Flotation (DAF) including chemical treatment;
3. Secondary biological treatment by Activated Sludge Process (Single Sludge Concept);
4. Secondary clarification by DAF including chemicals addition;
5. Filtration combined with DAF unit (DAFF);
6. Chlorination.

New developments in the field of physical-chemical treatment methods make the cost for combined physicochemical and biological plant comparable and more economical than a conventional biological treatment plant. The sedimentation unit, which requires a large area due to long detention times, and separate coagulation and
flocculation basins, can be replaced by a DAF clarifier. This replacement would significantly reduce capital investments and operation and maintenance (O&M) costs. The types of treatment processes involved in a physicochemical treatment plant design can be replaced by compact more efficient technologies, which can significantly improve secondary biologically treatment process, shorten detention time and sequentially decrease cost of this most expensive stage as well as overall O&M cost of whole municipal WWTP.

2.3. Preliminary Treatment

The first unit operation in wastewater treatment plants is screening. The screens are used to retain the coarse solids found in wastewater by interception. Typically, applied screens have openings 5/8 in (15mm) or less – fine screens. They can remove from 5 to 15 % of influent Total Suspended Solids (TSS) [3].

Grit removal are accomplished in grit chambers, which are designed to remove heavy solid materials that have subsiding velocities or specific gravities substantially greater than those of the organic putrescible solids in wastewater. Generally, the installation of screening facilities ahead of the grit chambers makes the operation and maintenance of the grit removal facilities easier.

Improvement of the preliminary treatment can be achieved by installation of the fine screen after grit chamber followed by the separate facilities for primary sludge disposal.
2.4. Primary DAF Clarification

Primary clarification includes coagulation and flocculation of suspended particles (SS) and removal of SS by a clarification unit operation like flotation or sedimentation, before secondary treatment.

Coagulation involves the destabilization of the colloidal particles, and flocculation involves the transport of the destabilized particles, which brought into contact with each other creating larger forms [4]. The use of chemicals significantly improves the coagulation-flocculation processes. Coagulant aids and polymers play a key role in water/wastewater physicochemical treatment processes. However, prior to use, the optimum dosage of the chemical or the chemical mix needs to be evaluated for the process conditions. Excessive chemical dosage may destabilize colloid particles, decrease quality of the clarifier effluent. Determining the most effective chemistry at the optimal dosage is the most important and time-dependent aspect of the DAF clarification process.

Dissolved Air Flotation (DAF) is one of the most efficient methods for the purpose of solid/liquid separation – clarification. The term refers to the method of producing flotation by dissolving air in the water under pressure (65-95 psig) and then subsequent releasing of the pressure (to 1 atm.). By the pressure release under laminar flow conditions, the water becomes supersaturated with air, and extremely fine air bubbles (20-80 µm) are generated. The air micro-bubbles attach to particles (as result of physical entrapment, electrochemical attraction, surface adsorption, and/or gas stripping) in the suspension, thereby decreasing their specific gravity. Through buoyancy force these particles float to the surface, where then they are collected and removed [5, 6]. The vertical rising rate of floated material is high and total detention time of DAF process takes around 3 min, which makes the technology very productive in terms of high overflow flow rate and low surface area requirement.

All chemical (coagulation, flocculation) and physical (solids/liquid separation) requirements of clarification is successfully achieved in one innovative KROFTA DAF unit [7], which makes the technology very compact and economically beneficial.
The feasibility of using DAF technology for primary clarification of municipal waste water has been positively demonstrated in pilot-scale studies in Kirklin WWTP (Kirklin, IN): average suspended solids reduction was 72%, BOD$_3$ removal was 65% [8]. The data of pilot study at the WWTP in Lee (Massachusetts) conducted by Lenox Institute of Water Technology gave the detail picture of primary DAF clarification performance: 76.6% of TSS, 48% of COD, 49% of BOD$_5$, 25% of Total P and 20% of TKN were removed from raw municipal wastewater using only polymer [9].

Primary DAF clarification is superior to conventional sedimentation (in case, if such system is applied). By flotation technology at least 40% of BOD$_5$ and 40% of TSS would be removed from the influent within very short period of time (few minutes) opposite to the same efficiency of sedimentation within 2-4 hours. Therefore, solids loading and organic loading to the secondary biologically treatment will be much less. The treatment task of biological reactor will be simplified as well as more efficient.

### 2.5. Secondary Treatment

The various biological processes (Activated Sludge, Trickling Filter, Rotating Biological Contractors, Sequencing Batch Reactors et.al.) can be applied as a biological treatment in municipal wastewater purification. The major objective of the biological treatment is to reduce the organic content and the nutrients such as nitrogen and phosphorus from water. Combination of biological treatment and secondary clarification is termed “secondary treatment”.

The removal of carbonaceous BOD, stabilization of organic matter and utilizing of nutrients are accomplished biologically using a variety of microorganisms: fungi, protozoa, metazoa and mostly bacteria. The microorganisms are used to convert the colloidal and dissolved carbonaceous organic matter into various gases and into cell tissue (dead cellular material).
Basic to the design of a biological treatment process or to the selection of the type of process to be used are the types of the biochemical activities of the important microorganism (microbial metabolism). For metabolism (function and reproducing) an organism must have a source of energy, carbon for synthesis of new cellular material and inorganic elements (nutrients) such as nitrogen, phosphorus, sulfur, potassium, calcium and magnesium.

There are two types of the most common sources of cell carbon for microorganisms: (1) organic matter and (2) carbon dioxide. Organisms that use organic carbon for the formation of cell tissue are called heterotrophs. Organisms that derive cell carbon from carbon dioxide are called autotrophs. The conversion of carbon dioxide to organic cell tissue is a reduction process that requires a net input of energy. Autotrophic organisms must therefore spend more of their energy for synthesis than do heterotrophs, resulting in generally lower growth rates among the autotrophs. The energy needed for cell synthesis may be supplied by light (phototrophs) or by chemical oxidation reaction (chemotrophs). Chemotrophs such as protozoa, fungi and most bacteria are heterotrophic, nitrifying bacteria are autotrophic. Chemoautotrophs obtain energy from the oxidation of reduced inorganic compounds such as ammonia, nitrite, and sulfide. Chemoheterotrophs usually derive their energy from the oxidation of organic matter. Chemoheterotrophic organisms may be further grouped according to their metabolic type and their requirement of molecular oxygen: 1) respiratory metabolism – generating energy is involved; enzyme-mediated electron transports from an electron donor to an external electron acceptor; 2) fermentation metabolism – external electron acceptor is not involved; process is less energy efficient, as a result fermentative heterotrophic organisms are characterized by low growth rate then respiratory heterotrophs. Organisms that use molecular oxygen in respiratory metabolism (aerobic respiration) are aerobic. Oxidized inorganic compounds such as nitrate and nitrite can function as electron acceptors for some respiratory organisms in the absence of molecular oxygenation – anoxic process conditions. Organisms that generate energy by fermentation and can exist only in an environment without oxygen are anaerobic.
2.5.1. Activated Sludge Process

Among the variety of the biological treatment processes, the activated sludge is currently the most popular in municipal wastewaters treatment. An activated sludge process is defined as system in which biological flocs (matrices of microorganisms, nonliving organic matter, and inorganic materials) are continuously circulated to come into contact and to oxidize the organic substances in the presence of oxygen [10]. The “active” mass of biological forms is maintained in suspended-growth state in the system.

Operationally, biological waste treatment by activated sludge process is typically accomplished using flow diagram in Figure 1 (conventional WWTP).

In aeration tank the bacteria culture carries out the conversion of biodegradable organics to inorganics.

Oxidation and synthesis:

\[
COHNS + O_2 + \text{nutrients} \xrightarrow{\text{bacteria}} \text{CO}_2 + \text{NH}_3 + C_5H_7NO_2 + \text{other end products}
\]

(organic matter) (new bacterial cell)

Endogenous respiration:

\[
C_5H_7NO_2 + 5O_2 \xrightarrow{\text{bacteria}} 5\text{CO}_2 + 2H_2O + \text{NH}_3 / NH_4^+ + \text{energy}
\]

(cells)

represent the first stage – (a) Carbonaceous oxidation – in which organic carbon is oxidized to carbon dioxide and (b) Ammonification – in which organic nitrogen is converted to the ammonium (NH\textsubscript{3}/ NH\textsubscript{4}\textsuperscript{+}) form under aerobic conditions.

Further biological Nitrogen removal occurs in the processes of Nitrification and Denitrification.

The two principal groups of microorganisms of importance in biological nitrification process are *Nitrosomonas* and *Nitrobacter*. Both of these groups are classified as autotrophic organisms, which utilize inorganic nitrogen as a source of energy for growth and inorganic carbon (CO\textsubscript{2}) for synthesis. Each group is limited to the oxidation of specific species of nitrogen compounds. *Nitrosomaonas* can oxidize
ammonia to nitrite, but cannot complete the oxidation to nitrate. On the other hand, *Nitrobacter* is limited to the oxidation of nitrite to nitrate [11]. Since complete nitrification is a sequential reaction (two-steps):

$$\begin{align*}
NH_4^+ + \frac{3}{2} O_2 & \xrightarrow{\text{Nitrosomonas}} NO_2^- + 2 H^+ + H_2O ; \\
NO_2^- + \frac{1}{2} O_2 & \xrightarrow{\text{Nitrobacter}} NO_3^- .
\end{align*}$$

The overall energy reaction is represented in the next equation:

$$\begin{align*}
NH_4^+ + 2 O_2 & \xrightarrow{\text{Nitrifiers}} NO_3^- + 2 H^+ + H_2O .
\end{align*}$$

The treatment process must be designed to provide an environment suitable to the growth of both groups of nitrifying bacteria. Approximately 4.3 mg of O_2 per 1 mg of NH_3-N oxidized to NO_2^- is needed. In the conversion process, a large amount of alkalinity is consumed: 8.64 HCO_3^- per 1 mg of ammonia-nitrogen oxidized. It should be noted that changing ammonia-nitrogen to nitrate-nitrogen does not facilitate nitrogen removal but does eliminate its oxygen demand [11].

Nitrifying bacteria are sensitive organisms and extremely susceptible to a wide variety of inhibitors. A variety of organic and inorganic agents can inhibit the growth and action of these organisms. A narrow optimal pH range between pH 7.5 – 8.6 exists, but system acclimated to lower pH conditions have successfully nitrified. Temperature also exerts a tremendous influence on the growth of nitrifying bacteria. Dissolved Oxygen (DO) concentration above 1 mg/L is essential, low DO becomes limiting parameter for nitrification process.

The removal of nitrogen in the form of nitrate by conversion to nitrogen gas can be accomplished biologically under anoxic conditions in the process of denitrification (anaerobic denitrification). Conversion of nitrate-nitrogen to a readily removable form can be accomplished by several groups of bacteria: *Achromobacter, Aerobacter, Alcaligenes, Bacillus, Brevibacterium, Flavobacterium, Lactobacillus, Micrococcus, Proteus, Pseudomonas* and *Spirillum*. These bacteria are heterotrophs capable of dissimilatory nitrate reduction, a two-step process. The first step is conversion of nitrate
to nitrite. The second step carries nitrite through two intermediates (nitric oxide, nitrous oxide) to nitrogen gas:

\[ \text{NO}_3^- \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2. \]

The last three compounds are gaseous products that can be released to the atmosphere.

The conversion to nitrogen gas is promoted by electrons passing from the carbon source (the electron donor) to nitrate or nitrite (the electron acceptor). This involves the nitrifiers “electron transport system” and is involved with the release of energy from the carbon source for use in organism growth.

The overall transformation for denitrification can be represented as follows:

\[ \text{NO}_3^- + \text{Carbon Source} \rightarrow \text{N}_2 \uparrow + \text{CO}_2 \uparrow + \text{H}_2\text{O} \]

(Nitrate) (Nitrogen Gas)

Usually, the nitrified effluent still contains a high enough amount of organic carbon in form of BOD, which will be sufficient for the following denitrification process. Otherwise, a supplemental source of carbon must be provided. Methanol, rather than any other organic, has seen widest use as the electron donor, as an additional carbon source in the U.S.

In denitrifying system DO concentration is a critical parameter. The presence of DO will suppress the enzyme system needed for denitrification. Alkalinity is produced during the conversion of nitrate to nitrogen gas resulting in an increase in pH. The optimal pH lies between 7-8. There are different optimums for different bacterial populations. Temperature affects the removal rate of nitrate and the microbial growth rate. The organisms are highly sensitive to changes in temperature.
2.5.3. Phosphorus Removal

Phosphorus appears in wastewater as orthophosphate (PO$_4^{3-}$), polyphosphate (P$_2$O$_7$), and organically bound phosphorus. The last two components may account for up to 70% of influent phosphorus. Microbes utilize phosphorus during cell synthesis and energy transport. As a result, 10 to 30% of the influent phosphorus is removed during secondary biological treatment. Additional uptake beyond that needed for normal cell maintenance and synthesis is required to achieve low effluent concentration levels. Under certain aerobic conditions more phosphorus than is needed may be taken up by the microorganisms. Phosphorus may be released from cell under anoxic conditions.

\[
\text{OrganicP} \rightarrow \text{orthophosphates} - PO_4^{3-} \rightarrow \text{polyphosphates} - P_2O_7
\]

Anaerobic conditions (Phosphorus Release)
Aerobic conditions (Phosphorus Uptake)

\[\text{Acinobacter}\] are one of the primary organisms responsible for removal of phosphorus. These organisms respond to volatile fatty acids (VFAs) in the influent wastewater under anaerobic conditions and will release stored phosphorus. The VFAs are an important substrate for the \textit{Acinobacter} during competition with heterotrophs. When an anaerobic zone is followed by an aerobic (oxic) zone, the microorganisms exhibit phosphorus uptake above normal levels. Phosphorus is not only utilized for cell maintenance, synthesis and energy transport but also stored for subsequent use by the microorganisms. The sludge containing the excess phosphorus is either wasted or removed and treated in side stream to release the excess phosphorus. Release of phosphorus occurs under anoxic conditions. Thus, biological phosphorus removal requires both: anaerobic and aerobic reactors or zones within a reactor.
2.5.4. Application of the Biological Treatment Processes

The carbonaceous oxidation, nitrification, denitrification (nitrogen and phosphorus removal) can be achieved in various types of activated sludge systems. The conventional approach to this task is realized in Three-Sludge Process (Figure 3, a). In the three-sludge process, carbon oxidation, nitrification and denitrification occur in three separate reactors [11]. In the first reactor, TSS and carbonaceous COD are removed under aerobic conditions. Typically, the soluble COD in the effluent from such reactor is 20 to 50 mg/L. The first stage reactor is followed by an intermediate clarifier. The settled effluent from the intermediate clarifier flows into a second aerobic reactor where ammonia is sequentially oxidized into nitrites and then to nitrates. This is nitrification activated sludge reactor, which is also following by second intermediate clarifier. The settled effluent from second clarifier flows into an anoxic reactor, where nitrates are denitrified into nitrogen gas. The anoxic reactor is followed by a final clarifier. Because most of the biodegradable soluble COD (BOD) present in the influent wastewater is removed in the upstream aerobic reactors, a supplemental organic carbon source such as methanol must be added to the anoxic reactor to accomplish denitrification.

Single-Sludge Concept

All nitrogen removal processes can be combined with carbon oxidation, ammonia oxidation and nitrate reduction in modified version of the activated sludge – Single Sludge System (Figure 3, b). All biological treatment stages occur in the same reactor under different environmental conditions: continuous flow (aerobic and anoxic zones); in batch system anoxic conditions is achieved by shutting down air feeding line. All biochemical reaction involved in organic oxidation, nutrients (nitrogen and phosphorus) removal was undergoing by action of the Mixed Culture of microorganisms [25]. Also, opposite to the traditional concept of nitrogen removal nitrification and denitrification can occur simultaneously under same conditions [26].

The preceding discussions about Three-Sludge process was concerned a single population of microorganisms in each separate reactor. But most biological treatment
Figure 3. Three Sludge System (a) vs. Single Sludge Concept (b)
processes are comprised of complex, interrelated, mixed biological populations (mixed culture), with each particular microorganism in the system having its own growth curve. The growth of the particular organism depends on the food and nutrients available and on environmental factors such as temperature, pH, and whether the system is aerobic or anaerobic. Sequentially, by changing the environment in the reactor the “active” microorganism’s population can be changed, originated from common complex mixed culture.

The treatment by single-sludge system also is followed by single secondary clarifier for biological sludge separation. The advantages, especially, economical benefit of such system are feasible.

**Contact Stabilization Process**

The 24-hours aeration conventional extended aeration activated sludge system is proposed to replace with innovative process using Contact Stabilization approach. When activated sludge is contacted with waste water in the aeration tank an initial rapid removal of organic matter occur, during very short period of time (20-40 min.) much colloidal and suspended organic matter, and some dissolved organic are adsorbed by the sludge flocs to some extend [10]. This adsorption phenomenon is used to improve the rate of biodegradation of organic matter in the innovative biological treatment system. Additional stabilization tank is included in the flow diagram (Figure 2) for returned (separated in secondary clarifier) sludge aeration, where during 1-2 hours organic matter is stabilized (synthesized and oxidized), returned sludge again “reactivated”.
2.6. Secondary Clarification

Unless the cell tissue produced from the organic matter is removed from the solution, complete treatment has not be accomplished because the cell tissue, which itself is organic, will be measured as BOD in the effluent. If the cell tissue is not removed, the only treatment that has been achieved is that associated with bacterial conversion of a portion of the organic matter originally present to various gaseous end products.

For separation of purified liquid and dead cellular material after completed biological treatment the DAF process is proposed to replace conventional gravity settling clarification.

The most common operational difficulties encountered in the conventional biological treatment plant are rising sludge and bulking sludge, resulting in high suspended solids and BOD₅ in the plant effluent. Such problems are caused by the growth of filamentous organisms [13]; formation of swelling biological flocs through the addition of bound water to the cell to extent that their density is reduced; increased buoyancy caused by nitrogen gas bubbles rising after denitrification. Introducing DAF for secondary clarification can be overcome these problems, and also use their benefit for sludge flotation [9]. DAF application on a pilot study at Patapsco Wastewater Plant, Baltimore, MD, gave excellent results on floating of biological activated sludge flocs, producing a sludge of high consistency (up to 4%) and average solids capture of 96% [8]. This results in the following improvements: reducing of hydraulic loading on biological reactor; higher solids content of waste sludge; the return sludge, separated by flotation is “fresh”, contains more dissolved oxygen, it is more active then settled sludge; oxygen requirements for the mixed liquor suspended solids is also reduced.

Therefore, for design of new activated sludge treatment process, either secondary flotation [14] and Sandfloat process [15, 16] shall be considered as a replacement of secondary sedimentation for elimination of possible sludge bulking and sludge rising problems, Sandfloat is an improved secondary flotation clarifier with a built-in multimedia filter. The quality of Sandfloat effluent will also far exceed the required secondary effluent standards.
2.7. Ammonia-nitrogen Removal by Chlorination

When chlorine is added to dilute aqueous solutions containing ammonia nitrogen, reactions occur which may lead ultimately to oxidation of the ammonium ions to end products composed predominately of nitrogen gas. When such chemical processes are performed in water and wastewater treatment for the purpose of ammonia nitrogen removal, the procedure is termed breakpoint chlorination.

The process chemistry is described by following reactions:

\[ \text{Cl}_2 + H_2O \leftrightarrow HOCl + H^+ + Cl^- \]

\[ NH_4^+ + HOCl \rightarrow NH_2Cl(\text{monochloramine}) + H_2O + H^+ \]

\[ NH_4^+ + HOCl \rightarrow NHCl_2(\text{dichloramine}) + H_2O \]

\[ NH_2Cl + NHCl_2 + 3H_2O \rightarrow N_2 + 3H_3O^+ + 3Cl^- \]

After completion of the last chemical reaction (chloramines oxidation) the breakpoint is achieved. Further addition of chlorine beyond the breakpoint yields an increasing residual of free chlorine.

Stoichiometrically, the breakpoint reaction requires the weight ratio of chlorine to ammonia nitrogen at the breakpoint of 7.6:1. In practice, the actual weight ratio of chlorine to ammonia nitrogen at breakpoint has ranged from about 8:1 to 10:1 [3, 4, 11]. With proper control and flow equalization, all ammonia nitrogen in the wastewater can be reduced to zero. Several application of breakpoint chlorination tests on domestic wastewater showed that 95-99% of ammonia nitrogen is removed [17, 18, 19]. Interferences to simplistic reaction cause higher chlorine demand and less than 100% ammonia-nitrogen reduction.

For chlorination after secondary clarification the chlorine contact channel, chamber or basin is required to provide sufficient contact time (15-30 min).
2.8. Low Temperature Effect on the Combined Physical-Chemical and Biological Treatment Process

Due to operation of Municipal Wastewater Treatment Plants in different climatic zones and at winter condition (Lee, Western Massachusetts, in winter air temperature can drop below -30°C), involving biological processes into domestic sewage treatment it is required to consider temperature as one of the most significant factors effecting treatment system performance and as a design limiting parameter. For activated sludge treatment plants freezing are not observed and lowest temperature of winter operation is ~8°C [23].

For the physicochemical part of treatment temperature does not play very important role. Of cause, due to temperature decreasing the solubility of chemical substances added to the wastewater will decrease [24], but the solubility of pollutant in the wastewater also will be limited. As a result, no significant effect of low winter temperatures on this stage of municipal waste treatment is expected.

Major and medium chain of the Combined system – biological treatment is the most sensitive and effected by the temperature lowering. In this case, the general rule works: temperature decreasing on 10 °C two-times lowers the rate of the biochemical reaction [4].

Under these cold temperatures (8 °C) the concentration of viable microorganisms in the mixed liquor appears to be approximately 25-40% lower than at normal operating conditions (20 °C). Lower concentration of viable organisms associated with lower specific removal rates at low temperatures would require maintaining substantially higher mixed liquor concentrations and/or increasing detention time to achieve similar removals [23]. The most temperature dependent microorganism are nitrogen-converting bacteria. The optimum temperature condition for *Nitrosomonas* and *Nitrobacter* are 30-35 °C. According to an investigation performed in Julich Institute of Biotechnology (Germany) the rate of ammonia-nitrogen oxidation by *Nitrosomonas* bacteria from 35 °C to 5°C drops approximately 60 times [27].
CHAPTER III

EXPERIMENTAL PROCEDURES

3.1. Process Procedures

1. The grit chamber effluent (about 20 gallons) and aeration basin mixed liquor (ML) (about 20 gallons) are collected from the Lee Waste Water Treatment Facilities. Air and water temperature are recorded. The small sample of the grit chamber effluent is taken for preliminary laboratory testing on COD content (around 300 mg/L). Then both samples are taken for a set of standard water quality analysis: pH, TSS, BOD₅, COD, TKN, NO₂-N, NO₃-N, NH₃-N, Total P. For analysis on nitrogen content the samples are filtered through the filter pad (1.5 μm).

2. Large portions of the grit chamber effluent and aeration basin mixed liquor (ML) are kept in a refrigerator to lower their temperatures to about 5 °C. Record Temperature of wastewater and aeration basin ML.

3. Then the aeration basin ML is settled for one hour and the supernatant is drained. Settled activated sludge is saved. The percent volume of settled activated sludge is recorded. It is assumed that the settled activated sludge represents the return activated sludge (RAS). Then RAS is aerated for about 1-2 hours simulating contact stabilization process. The RAS volume is recorded.

4. For elevation of low strength Lee wastewater to meet design criteria set by SEA (Town of Lee consulting engineers) and European consulting engineers (BOD₅ = 250 mg/L, TSS = 250 mg/L, NH₃-N = 25 mg/L) the outlined Spiking Procedure is used (below).

5. The fine 1/8 inch openings screen is used to screen the grit chamber effluent. The screened sample is taken for the set of standard water quality analysis.
6. The screened wastewater (more than 10 gallons) is treated by primary DAF with adequate coagulant/flocculant (best chemicals and optimum dosage). Sample of primary DAF effluent is collected for standard testing. The sludge volume and concentration, DAF %-recycle, and chemical treatment are recorded.

7. Known volume of the primary DAF effluent (about 10 gallons) and known volume of RAS (from 15 gallons of aerated basin ML) are mixed together. The volumetric ratio of primary DAF effluent vs. RAS is recorded. It should give a MLSS in the range of 3000-4000 mg/L.

8. The obtained primary DAF effluent & RAS mixture is treated aerobically. Mixed Liquor Dissolved Oxygen (MLDO) during aeration is kept at 3 mg/L or slightly higher. Cooling reactor is used to keep the temperature of ML around 5 °C for simulation of the cold weather condition. If it is required, MgO is used in order to adjust the pH of ML in optimum range pH 6.5-8 for aeration stage and pH 7.4-8.6 for anoxic condition - denitrification step. The duplicate ML samples at 1 hour, 2 hours and every hour up to 11 hours of detention time (DT) are taken until Carbonaceous Oxidation and Nitrification are completed. The first ML sample is filtered immediately using the filter pads and collects for standard testing. The second one is settled for 15 min. and supernatant is collected for standard testing. The laboratory analysis on COD and BOD content are performed on both samples (filtered and settled). The TKN and total P are analyzed only on settled samples. Settled and filtered samples are refrigerated for laboratory testing.

9. Immediately after 2-11 hours of carbonaceous oxidation and nitrification under aerobic conditions, the aeration is stopped by turning off the air supply, but slow mixing of ML is continued to keep MLDO below 1 mg/L. The ML temperature is monitored and kept around 5 °C. The ML samples at 20, 40, 60, 80, 120, 180 and 300 minutes of DT are taken until denitrification is completed. The duplicate ML samples are taken and then processed in the same way as for previous stage.
10. At the end of the denitrification step (3-5 hours), unfiltered ML is collected for plain sedimentation and secondary DAF clarification using: a) polymer only at optimized dosage; b) coagulant following by polymer at optimized dosage. All effluent samples are collected for the set of the standard water quality analysis. Sludge volume and concentration, DAF %-recycle are recorded.

11. DAF effluent is collected and filtered through coarse filter paper (30 μm) simulating sand filtration for final effluent polishing. Filtered liquid is collected for the set of standard water quality testing.

12. The filtrate is chlorinated using low dosage of chlorine (20-30 mg/L) for excess ammonia-nitrogen removal. NH₃-N content, pH and temperature are monitored and recorded.

The laboratory bench-scale simulation of treatment process of municipal wastewater under cold weather conditions is then completed.

### 3.1.1 Sample Preparation and Calibration

Treatment of the typical Lee WWTF influent wastewater and spiked Lee wastewater has been investigated to determine the treatment efficiency for “typical” case and “worst” (design) case under worst weather condition.

Typical Lee WWTF influent wastewater composition:
- BOD₅ = 130-157 mg/L;
- TSS = 80-133 mg/L;
- NH₃-N ~ 17 mg/L.

Therefore, to meet design criteria set by SEA (BOD₅ = 250 mg/L, TSS = 250 mg/L, NH₃-N = 25 mg/L) the wastewater sample spiking has been performed.

A BOD₅ feeding source Dry Milk (pure protein) “Nestle-Carnation” was used. Representing by themselves as the pollutants with high organic content, milk wastes proteins are widely present in domestic sewage. For determination of organic requirement for wastewater sample spiking, a detailed study of dry milk content vs. COD and BOD₅.
has been performed. The calibration curves of COD and BOD₅ are presented in Figure 4 and Figure 5 respectively. Also, for evaluation of needed milk dosage for spiking purpose the additional curve COD vs. BOD₅ has been plotted in Figure 6.

As NH₃-N feeding source, AMMONIA-cleaner “Parsons” was used. Like a pollutant, it contains high amount of NH₃-N, surfactants, different cleaning agents. It is widely used in housing, cleaning and sequentially, represented in municipal wastewater. Detail study of detergent dosage vs. ammonia-nitrogen content has been performed and also, followed by calibration curve plot (Figure 7).

For TSS content elevation the additional volume of raw Lee wastewater has been collected and then settled. Certain amount of settled sludge was added to raw wastewater to achieve design TSS content value.

3.2. Analytical Procedures

The set of laboratory analytical experiments were performed according to Standards Methods for the Examination of Water and Wastewater approved by U.S. Environmental Protection Agency [20, 21, 22]:

- **pH**
  - by Electrometric Method;

- **Dissolved Oxygen**
  - by Membrane Electrode Method;

- **Total Suspended Solids**
  - by TSS Dried at 103-105 °C Method;

- **Temperature**
  - by Laboratory and Field Methods;

- **Nitrite-Nitrogen**
  - by Diazotization Method;

- **Nitrate-Nitrogen**
  - by Cadmium Reduction Method;

- **Ammonia Nitrogen**
  - by Nessler Method;

- **Total Kjeldahl Nitrogen**
  - by Nessler Method with Digestion;

- **Biochemical Oxygen Demand**
  - by Dilution Method;

- **Chemical Oxygen Demand**
  - by Reactor Digestion Method;

- **Total Phosphorus**
  - by Persulfate Digestion Method.
Figure 4. Protein concentration vs. COD content
Figure 5. Protein concentration vs. BOD$_5$ content
Figure 5. COD vs. BOD₅ (dry milk - protein solution)
Figure 7. Detergent dosage vs. Ammonia-Nitrogen concentration
CHAPTER IV

EXPERIMENTAL APPARATUS

The feasibility of treating a wastewater stream by proposed Innovative Combined Physical-Chemical Process was accurately determined by conducting bench scale simulation in the laboratory. The simulation provides valuable information regarding the effectiveness of various water and wastewater treatment chemical combinations and is rapid and reliable means of observing changes made to process variables.

4.1. Screening Simulation

In screening procedure the fine screen 1/8 inch applied. Screened effluent is collected in 15 gallons Nalgene basket.

4.2. Dissolved Air Flotation Simulation

The principal equipment components required for DAF simulation are the flotation cylinder and air dissolving tank (canister).

The flotation cylinder is a modified 1000 ml Nalgene graduated cylinder. The plastic base is drilled in the cylinder bottom and then tapped for subnatant drain. Nalgene hose is attached to the drain and pinch clamp is placed on the hose. Cylinder is supported by a clamp attached to a standard laboratory ring stand.

The air dissolving canister (tank) is one gallon poly-construction multipurpose garden sprayer. The internal pump should be screw-in type. The nozzle and adjustable sleeve are removed from the delivery wand.

The DAF unit can be operated under three different conditions: full flow pressurization, partial flow pressurization and recycle flow pressurization.
On the experiment the recycle flow pressurization mode was applied, under which conditions KROFTA Supracell DAF is usually operated.

Determining the most effective chemistry at the optimal dosage is a very important aspect of the DAF simulation. Chemical dosing can be conducted in 20 ml Workups using 50 ml test tube and then in 1000 ml Workups using beakers and Standard Jar Test Apparatus. Most effective chemistry is determined within the set of metallic coagulant aids and organic polymers.

Additional instruments: stop-watch and ruler is required for flotation rate determining.

The DAF simulation is performed according to the procedure outlined in the Laboratory Manual for Water and Wastewater Analysis of LIWT and in the paper [28].

4.3. Sedimentation Simulation

The bench scale sedimentation test is performed in 1 liter Imhoff Cone for 1-hour settling period. The cone is supported by a clamp attached to a standard laboratory ring stand.

4.4. Simulation of Biological Treatment under Cold Weather Conditions

For biological study under cold weather conditions a special cooling reactor was constructed (Figure 8). The experimental set up consists of two Nalgene containers: a smaller one (15 gallons) and a bigger one (30 gallons), introduced one into another creating free space between walls. This space is filled by cold water and ice (as cooling agent). Excess amount of cooling water after ice melting can be drained from the cooling system through valve tapped to the bottom of big container. Because of sufficient long time of ice melting such a system is expected to give high performance in thermostabilization near 5-7 °C, which is required by conditions of the experiment.
Figure 8. Schematic picture of cooling biological reactor
The volume of the smaller reactor is filled by Primary DAF effluent and RAS creating activated sludge Mixed Liquor. ML mixing regime was performed by Barnant Mixer, Series 20 Model No.700-5410, VWR Scientific Product. To keep DO around 3 mg/L to supply aerobic environment for oxidation and nitrification, the airline inside reactor was installed. Air micro-bubbles were released though the fine porous material of the air diffuser supplying efficient source of DO to the ML.

The environment inside the reactor was monitored using Dissolved Oxygen Meter, SI Model 51 B and EC10 portable pH/mV/Temperature Meter, Model 50050, HACH Company.

Simulation of Contact Stabilization Activated Sludge Process involved additional tank (5 gallons Nalgene basket) for RAS stabilization. Into stabilization tank, the air line with diffuser also was installed for sludge aeration for a period of 1-2 hours.

4.5. Filtration Simulation

For purpose of filtration the coarse filter paper (30 μm) was used, simulating filtration through the sand media in KROFTA DAF+Filtration unit. Filter pad is placed into laboratory funnel (Ø = 10 cm), which is supported by a clamp attached to a standard laboratory ring stand. Filtered liquid is collected into the beaker.

4.6. Chlorine Contact Simulation

In bench batch experiment, chlorination was accomplished by addition of the chlorine compound sodium hypochlorite (5.25 % NaOCl) to filtered DAF effluent sample in the settling cone in an amount sufficient to oxidize ammonia to nitrogen gas. In practice, ratio 10 mg/L of Chlorine is required for every 1 mg/L of NH₃-N.
CHAPTER V

EXPERIMENTAL RESULTS

5.1. Treatment of Unspiked Lee Wastewater at 8 °C

Experimental conditions and results of the first Combined Physical-Chemical and Biological study are presented in following Data Sheet and Table 1. Temperature 8 °C was advised by consulting engineers for cold weather study providing the most challenging operational conditions for biological treatment process operation.
EXPERIMENT #1

Study of Combined Physical-Chemical and Biological Treatment under Simulated Cold Weather Conditions

Lee Waste Water Treatment Plant sampling data:

Grit Chamber Data: Date Sampled = 01/04/00 Time Sampled = 9:02 AM Air Temp = 5°C Water Temp = 9°C
Aeration Basin Data: Date Sampled = 01/04/00 Time Sampled = 9:15 AM Air Temp = 5°C Water Temp = 9°C

Activated Sludge Aerated for = 30 minutes. RAS Suspended Solids = 9,890 mg/L.
Volume of Settled Activated Sludge (from 10 Gallons) = 3 Gallons
Volume of Activated Sludge used to treat 10 Gallons of DAF Effluent = 2 Gallons

Primary Dissolved Air Flotation Treatment Data:
1. Chemical Treatment
   Coagulant = 80 ppm Eaglebrook Ferric Chloride
   Flocculant = 5 ppm SuperFloc A-1849 RS
   Recycle Rate = 25%
   Flotation Rate = 10 inches/1st minute
   Sludge Volume = 20 ml
   Sludge Concentration = 1.4%
   Chemical Cost = 11 cents/1000 gallons

Secondary Clarification Data:
1. DAF + Chemical treatment using polymer only
   Coagulant = Not Used
   Flocculant = 3 ppm Magnifloc 496C
   Recycle Rate = 25%
   Flotation Rate = 12 inches/1st minute
   Sludge Volume = 120 ml/L
   Sludge Concentration = 1.2%
   Chemical Cost = 5 cents /1000 Gallons

2. DAF + Chemical treatment using a coagulant followed by a polymer
   Coagulant = 100 ppm Aluminum Sulfate
   Flocculant = 3 ppm Magnifloc 496C
   Recycle Rate = 25%
   Flotation Rate = 12 inches/1st minute
   Sludge Volume = 100 ml/L
   Sludge Concentration = 1.4%
   Chemical Cost = 8 cents /1000 Gallons
<table>
<thead>
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<th></th>
<th>pH, units</th>
<th>DO, mg/L</th>
<th>TSS, mg/L</th>
<th>T, °C</th>
<th>NO$_3^-$, mg/L</th>
<th>NO$_2^-$, mg/L</th>
<th>NH$_3$-N, mg/L</th>
<th>TKN, mg/L</th>
<th>BOD$_5$, mg/L</th>
<th>COD, mg/L</th>
<th>Total P, mg/L</th>
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<tr>
<td>Raw</td>
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<td>-</td>
<td>214</td>
<td>9</td>
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<td>0.8</td>
<td>24.25</td>
<td>NT</td>
<td>144</td>
<td>353</td>
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<tr>
<td>Screened</td>
<td>7.57</td>
<td>-</td>
<td>186</td>
<td>9</td>
<td>0.030</td>
<td>0.7</td>
<td>20.75</td>
<td>38</td>
<td>147</td>
<td>320</td>
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<td>-</td>
<td>32</td>
<td>10</td>
<td>0.028</td>
<td>0.6</td>
<td>19.00</td>
<td>24</td>
<td>46</td>
<td>83</td>
<td>0.35</td>
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<tr>
<td>Activated Sludge</td>
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<td>-</td>
<td>2946</td>
<td>9</td>
<td>0.069</td>
<td>0.6</td>
<td>8.75</td>
<td>203</td>
<td>1374</td>
<td>3840</td>
<td>20.50</td>
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### Aerobic stage

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<th>Time</th>
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<th>TSS, mg/L</th>
<th>T, °C</th>
<th>NO$_3^-$, mg/L</th>
<th>NO$_2^-$, mg/L</th>
<th>NH$_3$-N, mg/L</th>
<th>TKN, mg/L</th>
<th>BOD$_5$, mg/L</th>
<th>COD, mg/L</th>
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<tbody>
<tr>
<td>0 time - F</td>
<td>6.52</td>
<td>11.0</td>
<td>1954</td>
<td>8</td>
<td>0.067</td>
<td>0.7</td>
<td>20.75</td>
<td>21</td>
<td>13</td>
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<tr>
<td>1 hour - F</td>
<td>7.22</td>
<td>4.6</td>
<td>2081</td>
<td>8</td>
<td>0.141</td>
<td>1.2</td>
<td>19.50</td>
<td>NT</td>
<td>5</td>
<td>33</td>
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<tr>
<td>2 hours - F</td>
<td>6.89</td>
<td>3.9</td>
<td>1906</td>
<td>8</td>
<td>0.186</td>
<td>1.6</td>
<td>16.75</td>
<td>NT</td>
<td>4</td>
<td>33</td>
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<td>3 hours - F</td>
<td>6.97</td>
<td>3.3</td>
<td>1845</td>
<td>8</td>
<td>0.276</td>
<td>1.9</td>
<td>16.10</td>
<td>16</td>
<td>2</td>
<td>17</td>
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<td>5 hours - F</td>
<td>6.89</td>
<td>3.5</td>
<td>1867</td>
<td>8</td>
<td>0.340</td>
<td>3.2</td>
<td>15.40</td>
<td>NT</td>
<td>&lt;2</td>
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<tr>
<td>8 hours - F</td>
<td>6.98</td>
<td>3.9</td>
<td>1955</td>
<td>8</td>
<td>0.614</td>
<td>5.2</td>
<td>15.10</td>
<td>NT</td>
<td>&lt;2</td>
<td>7</td>
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<tr>
<td>11 hours - F</td>
<td>6.95</td>
<td>4.1</td>
<td>1887</td>
<td>8</td>
<td>0.870</td>
<td>7.4</td>
<td>14.10</td>
<td>16</td>
<td>&lt;2</td>
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### Anoxic stage

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<th>T, °C</th>
<th>NO$_3^-$, mg/L</th>
<th>NO$_2^-$, mg/L</th>
<th>NH$_3$-N, mg/L</th>
<th>TKN, mg/L</th>
<th>BOD$_5$, mg/L</th>
<th>COD, mg/L</th>
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<tbody>
<tr>
<td>0 time - F</td>
<td>5.05</td>
<td>0.8</td>
<td>1915</td>
<td>8</td>
<td>0.905</td>
<td>8.0</td>
<td>13.80</td>
<td>13</td>
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<td>20 min. - F</td>
<td>6.70</td>
<td>0.1</td>
<td>1892</td>
<td>8</td>
<td>0.880</td>
<td>8.0</td>
<td>14.20</td>
<td>NT</td>
<td>&lt;2</td>
<td>31</td>
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<td>40 min. - F</td>
<td>5.99</td>
<td>0.2</td>
<td>1899</td>
<td>8</td>
<td>0.810</td>
<td>7.6</td>
<td>14.30</td>
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<td>&lt;2</td>
<td>28</td>
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<tr>
<td>60 min. - F</td>
<td>6.90</td>
<td>0.1</td>
<td>1949</td>
<td>8</td>
<td>0.780</td>
<td>7.6</td>
<td>13.80</td>
<td>11</td>
<td>&lt;2</td>
<td>21</td>
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<tr>
<td></td>
<td>pH, units</td>
<td>DO, mg/L</td>
<td>TSS, mg/L</td>
<td>T, °C</td>
<td>NO₂⁻, mg/L</td>
<td>NO₃⁻, mg/L</td>
<td>NH₄⁺-N, mg/L</td>
<td>TKN, mg/L</td>
<td>BOD₅, mg/L</td>
<td>COD, mg/L</td>
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<tr>
<td>--------------------</td>
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<tr>
<td>80 min. - F</td>
<td>6.38</td>
<td>0.1</td>
<td>1937</td>
<td>8</td>
<td>0.745</td>
<td>6.8</td>
<td>12.80</td>
<td>NT</td>
<td>&lt;2</td>
<td>24</td>
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<td>120 min. - F</td>
<td>6.91</td>
<td>0.2</td>
<td>1867</td>
<td>8</td>
<td>0.680</td>
<td>7.0</td>
<td>13.70</td>
<td>NT</td>
<td>&lt;2</td>
<td>24</td>
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<td>180 min. - F</td>
<td>6.77</td>
<td>0.2</td>
<td>1830</td>
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<td>0.655</td>
<td>6.2</td>
<td>13.30</td>
<td>13</td>
<td>&lt;2</td>
<td>32</td>
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<td>300 min. - F</td>
<td>6.92</td>
<td>0.2</td>
<td>1438</td>
<td>8</td>
<td>0.695</td>
<td>4.4</td>
<td>12.50</td>
<td>NT</td>
<td>&lt;2</td>
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<tr>
<td>Secondary DAF-effluent (Polymer only)</td>
<td>7.11</td>
<td>-</td>
<td>&lt;1</td>
<td>12</td>
<td>0.278</td>
<td>1.6</td>
<td>12.19</td>
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<td>-</td>
<td>&lt;1</td>
<td>12</td>
<td>0.269</td>
<td>1.3</td>
<td>11.13</td>
<td>NT</td>
<td>30</td>
<td>132</td>
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</table>

Note: F - filtered sample; NT - not tested
5.2. DAF Secondary Clarification

Detailed study of DAF application as the secondary clarification process has been performed to find out the optimal chemistry and chemical dosage, in turn to solve the problem of increased BOD₅ and COD content in final effluent at 99% of TSS removal at Experiment#1.

Experimental conditions and result are presented in Table 2.

Table 2

<table>
<thead>
<tr>
<th>Sample &amp; Experimental conditions</th>
<th>Temp., °C</th>
<th>pH</th>
<th>TSS, mg/L</th>
<th>COD mg/L</th>
<th>BOD₅, mg/L</th>
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<tbody>
<tr>
<td>1. Aeration basin effluent</td>
<td>9.1</td>
<td>6.57</td>
<td>2458</td>
<td>3277</td>
<td>930</td>
</tr>
<tr>
<td>2. ML composition</td>
<td>11.8</td>
<td>6.53</td>
<td>3269</td>
<td>4233</td>
<td>985</td>
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<tr>
<td>3. Filtration</td>
<td>16.3</td>
<td>7.21</td>
<td>-</td>
<td>30</td>
<td>&lt;2</td>
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<tr>
<td>(fiber-glass filter, 1.5 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Sedimentation:</td>
<td>17.5</td>
<td>7.05</td>
<td>10</td>
<td>39</td>
<td>5</td>
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<tr>
<td>settling rate = 1 in/1°min.</td>
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<tr>
<td>sludge volume = 500 ml</td>
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<td>sludge concentration = 0.7 %</td>
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<td></td>
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</tr>
<tr>
<td>retention time = 30 min.</td>
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<tr>
<td>13. DAF using Coagulant + Polymer: coagulant = 100 ppm FeCl₃ polymer = 2 ppm Superfloc A-130, 835 A recycle rate = 33% flotation rate = 8 in./l/min sludge volume = 180 ml sludge concentration = 1.8% chemicals cost = 13 cents/1000 gallons</td>
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<td>14. DAF using Coagulant + Polymer: coagulant = 100 ppm Fe₂(SO₄)₃ polymer = 2 ppm Superfloc 496 c recycle rate = 33% flotation rate = 8 in./l/min sludge volume = 200 ml sludge concentration = 1.6% chemicals cost = 13 cents/1000 gallons</td>
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<td>15. DAF using Coagulant + Polymer: coagulant = 100 ppm Fe₂(SO₄)₃ polymer = 2 ppm Superfloc Mx60 recycle rate = 33% flotation rate = 3 in./l/min sludge volume = 250 ml sludge concentration = 1.3% chemicals cost = 12 cents/1000 gallons</td>
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<td>16. Biological Flotation: Observation time = 2 hours</td>
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The tiny bubbles on the surface of the sludge appear carrying small solids to the surface of liquid. Visible floating layer of sludge was not observed, just random rising to the top solids.
5.3. Treatment of Unspiked Lee Wastewater at 5 °C

The Second Experiment was performed at lowest temperature, 5 °C, of ML in aeration basin, monitored in Lee WWTF.

For the secondary DAF clarification the most effective chemistry combination was applied. The every step of the innovative system performance was compared with conventional settling.

Experimental data are presented in Table 3.
EXPERIMENT #2
Study of Combined Physical-Chemical and Biological Treatment under Simulated Cold Weather Conditions

Lee Waste Water Treatment Plant sampling data:

Grit Chamber Data: Date Sampled = 02/16/00 Time Sampled = 9:06 AM Air Temp = 1°C Water Temp = 6°C
Aeration Basin Data: Date Sampled = 02/16/00 Time Sampled = 9:12 AM Air Temp = 1°C Water Temp = 6°C

Activated Sludge Aerated for = 60 minutes. RAS Suspended Solids = 12,600 mg/L.
Volume of Settled Activated Sludge (from 10 Gallons) = 4 Gallons
Volume of Activated Sludge used to treat 10 Gallons of DAF Effluent = 4 Gallons

Primary Dissolved Air Flotation Treatment Data:
1. Chemical Treatment
   Coagulant = 80 ppm Eaglebrook Ferric Chloride
   Flocculant = 5 ppm Superfloc A-1849 RS
   Recycle Rate = 25%
   Flotation Rate = 12 inches/1st minute
   Sludge Volume = 15 ml
   Sludge Concentration = 1.4%
   Chemical Cost = 11 cents/1000 gallons

Secondary Clarification Data:
1. Sedimentation:
   Detention time = 1 hour; Settling rate = ¼ inch/1st minute;
   Sludge volume = 446 ml Sludge concentration = 0.4%
2. DAF + Chemical treatment using polymer only
   Coagulant = Not Used
   Flocculant = 3 ppm Superfloc Mx60
   Recycle Rate = 33%
   Flotation Rate = 5 ½ inches/1st minute
   Sludge Volume = 250 ml/L
   Sludge Concentration = 0.7%
   Chemical Cost = 1 cents /1000 Gallons
2. DAF + Chemical treatment using a coagulant followed by a polymer
   Coagulant = 100 ppm Fe₂(SO₄)₃
   Flocculant = 2 ppm Superfloc Mx60
   Recycle Rate = 33%
   Flotation Rate = 8 1/2 inches/1st minute
   Sludge Volume = 200 ml/L
   Sludge Concentration = 0.9%
   Chemical Cost = 12 cents /1000 Gallons
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**Aerobic conditions**

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**Anoxic conditions**

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**Total P, mg/L**

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Note: S – settled sample; F – filtered sample; NT – not tested
5.4. Treatment of Spiked Lee Wastewater at 5 °C

The proposed innovative system was examined on treatment of the worst (full design loading) spiked Lee wastewater sample under worst weather condition. Experimental results are presented in Table 4.
EXPERIMENT #3

Study of Combined Physical-Chemical and Biological Treatment under Simulated Cold Weather Conditions

Lee Waste Water Treatment Plant sapling data:

Grit Chamber Data: Date Sampled = 03/20/00  Time Sampled = 9:03 AM  Air Temp = 4°C   Water Temp = 7°C
Aeration Basin Data: Date Sampled = 03/20/00  Time Sampled = 9:12 AM  Air Temp = 4°C   Water Temp = 7°C

Activated Sludge Aerated for = 60 minutes. RAS Suspended Solids = 1774 mg/L.
Volume of Settled Activated Sludge (from 15 Gallons) = 3.14 Gallons
Volume of Activated Sludge used to treat 10 Gallons of DAF Effluent = 2.75 Gallons

Primary Dissolved Air Flotation Treatment Data:

1. Chemical Treatment
   Coagulant = 80 ppm Eaglebrook Ferric Chloride
   Flocculant = 5 ppm Superfloc A-1849 RS
   Recycle Rate = 25 %
   Flotation Rate = 12 inches/1st minute
   Sludge Volume = 20 ml
   Sludge Concentration = 2.4%
   Chemical Cost = 11 cents/1000 gallons

Secondary Clarification Data:

2. Sedimentation:
   Detention time = 1 hour; Settling rate = ½ inch/1st minute;
   Sludge volume = 546 ml;  Sludge concentration = 0.7%

2. DAF + Chemical treatment using polymer only
   Coagulant = None Used
   Flocculant = 3 ppm Superfloc Mx60
   Recycle Rate = 33%
   Flotation Rate = 5 inches/1st minute
   Sludge Volume = 250 ml/L
   Sludge Concentration = 1.5%
   Chemical Cost = 1 cents/1000 Gallons

Chlorination: 63 mg/L of NaOCl (30 mg/L as chlorine);

2. DAF + Chemical treatment using a coagulant followed by a polymer
   Coagulant = 100 ppm Fe₂(SO₄)₃
   Flocculant = 2 ppm Superfloc Mx60
   Recycle Rate = 33%
   Flotation Rate = 7 inches/1st minute
   Sludge Volume = 250 ml/L
   Sludge Concentration = 1.5%
   Chemical Cost = 12 cents/1000 Gallons

Filtration: coarse filter paper – 30 μm openings
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**Aerobic conditions**

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Anoxic conditions

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Secondary Sedimentation

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Secondary DAF- effluent (Polymer only)

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Secondary DAF-effluent (Coagulant/polymer)

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<thead>
<tr>
<th>Time</th>
<th>pH, units</th>
<th>DO, mg/L</th>
<th>TSS, mg/L</th>
<th>T, °C</th>
<th>NO$_2^-$, mg/L</th>
<th>NO$_3^-$, mg/L</th>
<th>NH$_3$-N, mg/L</th>
<th>TKN, mg/L</th>
<th>BOD$_5$, mg/L</th>
<th>COD, mg/L</th>
<th>Total P, mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filtered</td>
<td>7.45</td>
<td>-</td>
<td>&lt;2</td>
<td>15.2</td>
<td>1.02</td>
<td>1.5</td>
<td>11.55</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Filtered

<table>
<thead>
<tr>
<th>Time</th>
<th>pH, units</th>
<th>DO, mg/L</th>
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<th>BOD$_5$, mg/L</th>
<th>COD, mg/L</th>
<th>Total P, mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH$_3$-N removal by Chlorination</td>
<td>7.67</td>
<td>-</td>
<td>-</td>
<td>20.3</td>
<td>-</td>
<td>-</td>
<td>6.25</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: F – filtered sample; S – settled sample; NT – no tested.
CHAPTER VI
DISCUSSION

Experiment results presented in the set of tables (Table 1, Table 2, Table 3, Table 4) express a broad picture of performance efficiency of a proposed innovative Combined Physicochemical and Biological System (DAF – aerobic – anoxic – DAF) for municipal wastewaters treatment. The data obtained after completing Experiment #2 (Table 3) show that a typical unspiked municipal wastewater (BOD$_5$/TSS/NH$_3$-N = 107 mg/L/160 mg/L/17 mg/L) can be properly treated by the innovative system in extremely short detention time (6 hours for bio-treatment) even at very low temperature (5°C), which is four times shorter than performance of conventional extended aeration biological system. All current NPDES effluent standards (Appendix A) for the Town of Lee were met. The NPDES discharge limitation for the future are very stringent (BOD$_5$/TSS/NH$_3$-N = 20 mg/L/20 mg/L/10 mg/L), as shown in Appendix B. The innovative system also met the new NDPES discharge limitation when treating the unspiked Lee wastewater.

Special experimental task or research challenge was to examine the treatment system efficiency using the spiked high strength wastewater influent with full influent design loading (BOD$_5$/TSS/NH$_3$-N = 250 mg/L/250 mg/L/25 mg/L) and try to meet more stringent discharge effluent limitation (BOD$_5$/TSS/NH$_3$-N = 20 mg/L/20 mg/L/10 mg/L). Detention time of biological treatment process was increased with increasing of the strength of treated waste stream, and with decreasing temperature of mixed liquor to 5°C (lowest temperature monitored during winter operation of Lee WWTF). Results of Experiment #3 presented in Table 4 show that treatment of elevated wastewater sample was completed within 12 hours by carbonaceous oxidation and nitrification (9 hours) and denitrification (3 hours). From this point of view the obtained results are very interesting and will be discussed in detail.
6.1. Primary Treatment Performance

Results of the Experiment #3 (Table 4) display high efficiency of the primary treatment. Successful introduction of fine screening and innovative DAF technology significantly reduce the loading to the biological treatment stage. It was estimated that the primary treatment removed 66% of TSS, 63% of BOD$_5$, 20% of total phosphorus and 40% of organic nitrogen.

As a whole, research demonstrated that primary DAF with chemical treatment and a recycle ratio of 25% could achieve 99% of TSS reduction, 99% of BOD$_5$ reduction and 79% of total phosphorus reduction.

6.2. Secondary Treatment Performance

Biological treatment of the elevated spiked Lee wastewater sample (BOD$_5$/ TSS / NH$_3$-N / total P = 255 mg/L / 257 mg/L / 24.5 mg/L / 19.2 mg/L) was extended to 9 hours of carbonaceous oxidation, nitrification and 3 hours of denitrification.

**Carbonaceous oxidation**

Experimental data plotted in Figure 9 show that during Experiment #3 (Table 4) carbonaceous oxidation was completed within 2 hours. BOD$_5$ reduction curve reaches the certain level which could be the limit of biological adsorption and oxidation. Remaining soluble BOD$_5$ content is not high and can be utilized in further denitrification stage as a carbon source. This is the benefit of a single sludge system over the three separate sludge system, in which biodegradable organics were completely removed in aerobic stages and sequentially external source of organic carbon is required for denitrification. In USA mostly methanol is used for this purpose, which significantly increases the costs of biological treatment. In general, the system did not meet difficulties with biodegradable organics removal, soluble BOD$_5$ content of biological treatment effluent is 12 mg/L.
Figure 9. BOD$_5$ reduction by Innovative Combined Physicochemical and Biological Treatment System under 5 °C (spiked sample)
Nitrogen removal

During the experiment there was a whole cycle of nitrogen transformation:

\[ \text{Organic } N \rightarrow NH_3-N \rightarrow NO_2-N \rightarrow NO_3-N \rightarrow N_2 \]

The innovative biological treatment system achieved both nitrification and denitrification even at low wastewater temperature.

During the nitrification process ammonia-nitrogen was measured every hour. Results are presented in Figure 11. At the beginning (first hour) ammonia-nitrogen increased rapidly due to organics oxidation and organic nitrogen ammonification. During the remaining 7 hours of aeration ammonia-nitrogen reached ~14 mg/L level and then was not changed significantly to the end of biological treatment.

Nitrification process performance was observed by nitrite and nitrate measurements (Figure 12). Ammonia-nitrogen decreasing led to a significant increase in nitrate nitrogen and a small increase in the amount of nitrite-nitrogen. The experimental results correlated very well.

Growth of nitrifies population was inhibited by low temperature, which explains high content (15.75 mg/L) of NH\textsubscript{3}-N in the biological treatment effluent. Even after chemical treatment and secondary DAF clarification, NH\textsubscript{3}-N was still higher than the allowed discharge limit concentration (10 mg/L). Additional chemical process for ammonia neutralization was required. In this research chlorination was applied to ammonia reduction. During the chlorination process breakpoint was not achieved, ammonia-nitrogen was removed completely and free residual chlorine was not detected. At a chlorine/NH\textsubscript{3}-N ratio of 10:1 only a small amount of chlorine was added to meet the effluent NH\textsubscript{3}-N limitation standard. All chlorine reacted with ammonia producing chloramines – disinfectants. Seasonal disinfection of biological treatment process effluent is required by the Commonwealth of Massachusetts regulations. A chlorine contact basin was proposed to be used after sand filtration. Filtered effluent did not contain high organics concentration (BOD\textsubscript{5}< 2 mg/L), the possibility of harmful chlorination by-products formation was minimized.
Figure 10. Ammonia-Nitrogen removal by Innovative Combined Physicochemical and Biological Treatment System under 5 °C (spiked sample)
Figure 11. Nitrite and Nitrate removal by Innovative Combined Physicochemical and Biological Treatment System under 5 °C (spiked sample)
Phosphorus removal

The experimental results for total phosphorus removal are presented in Figure 13. As one can see the phosphorus reduction by biological system was not effected by low temperatures. 85% of total phosphorus was absorbed by microorganisms within the first hour of treatment and utilized during cell synthesis and energy transport as supplemental nutrient. The remaining phosphorus content was accumulated and stored by cell matter and then removed from water by clarification as Suspended Solids.

6.3. Secondary Clarification

DAF efficiency for secondary biosolids harvesting was very high – 98-99%. The sludge bulking and rising phenomenon observed on the experiment, (Table 4), was easily overcome by DAF clarification.

Due to variation of raw wastewater compositions the most effective chemicals at optimum dosage (Table 2) can’t always produce excellent effluent quality to satisfy new final effluent regulations. High operational skills will be required to respond to the influent quality changes or chemical metering paced by zeta potential or other automatic methods.

Complete TSS removal can be achieved by filtration. The possibility of adopting a DAF-Filtration clarifier was taken into account. Such secondary DAF-Filtration installation will be more expensive than the secondary DAF alone, but will consistently produce a final effluent exceeding the government regulation. Adoption of DAF-Filtration for secondary clarification also will introduce an important factor of safety in WWTP operation.
Figure 12. Total Phosphorus removal by Innovative Combined Physicochemical and Biological Treatment System under 5 °C (spiked sample)
CHAPTER VII

CONCLUSIONS

- Existing conventional municipal wastewater treatment plants can be adequately upgraded to achieve compliance with their final National Pollutant Discharge Elimination System (NPDES) discharge requirements within their financial constraints, by adopting alternative innovative technologies for wastewater treatment.

- An alternative approach of treating municipal wastewater by a Combined Physical-Chemical-Biological Process system has been proven to be scientifically sound.

- Innovative Dissolved Air Flotation (DAF) is effective for primary and secondary clarification when applied to a biological treatment process plant to improve the overall treatment efficiency.

- The feasibility of using DAF as a primary clarifier for chemical treatment as well as clarification has been positively demonstrated: 44-99% of TSS reduction, average 66% of BOD$_5$ reduction and from up to 79% of total P reduction were achieved in this research.

- The new biological wastewater treatment system involving the use of contact stabilization flow diagram, Single-Sludge concept was developed for typical municipal wastewater treatment under cold weather conditions.

- All three stages of biological treatment process (carbonaceous oxidation, nitrification and denitrification) can be achieved in the same reactor for organics and nutrients removal under aerobic and anoxic conditions at low temperature (5-8 °C) and within short detention time (12 hours).
- The application of DAF as secondary clarifier can successfully solve the problems of the sludge rising and bulking in biosolids separation process after biological treatment with denitrification stage. The results indicate that at 33% of recycle ratio and with addition of low dosage of the polymer about 98-99% of TSS reduction was achieved. The effluent quality was excellent. But to meet new NPDES and Commonwealth of Massachusetts discharge requirements (TSS = 20 mg/L, BOD₅ = 20 mg/L, NH₃-N = 10 mg/L, Total P = 1 mg/L) and to provide a factor of safety, the final polishing of effluent by filtration is required. The combined DAF and filtration clarification can be achieved by adoption of an innovative DAF-Filtration technology, known as Sandfloat, or equivalent.

- Excess content of NH₃-N remaining after biological treatment was successfully removed by chlorination process.
REFERENCES


APPENDIXES

Appendix A

NPDES effluent limits for Lee WWTF (1999):

- Effluent BOD₃ limits = 30 mg/L or below;
- Effluent TSS limits = 30 mg/L or below;
- Effluent ammonia-nitrogen limits = none required by MA-DEP (10 mg/L reported by SEA).
Appendix B

EFFLUENT LIMITATION AND MONITORING REQUIREMENTS
by the Commonwealth of Massachusetts for the Town of Lee

- Effluent BOD$_5$ limits = 20 mg/L or below;
- Effluent TSS limits = 20 mg/L or below;
- Effluent total P = 0.7 mg/L or below;
- Effluent ammonia–nitrogen = 10 mg/L or below.