SIMULATING FULL-SCALE DRINKING WATER UNIT OPERATIONS ON PILOT-SCALE

by

Andreas Gruber-Waltl

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ABSTRACT

Pilot plant studies are crucial in water and wastewater treatment, to study processes on smaller scale before implementation to full-scale. As part of a partnership between the City of Golden (CO) and the Colorado School of Mines a pilot plant laboratory was established in the Golden Water Treatment Plant (GWTP).

The goal of this study was to design and construct a pilot plant, capable to simulate conventional and advanced water treatment unit operations, which are currently employed at the full-scale GWTP. In order to be able to conduct long-term studies, the pilot plant was designed for continuous operation, controllable from a remote location. The installed treatment processes comprise pre-oxidation, coagulation, flocculation, sedimentation and filtration with a dual media filter. Advanced water treatment processes like filtration with granulated activated carbon and membrane treatment were also integrated into the pilot plant.

The performance of the pilot plant unit operations were optimized, using tracer and baseline performance tests. The baseline tests determined the effectiveness of the selected coagulation and polymer concentrations, which corresponded to the full-scale plant. The results of a real time flocculation analyzer (FlocAnalyzer from ClearCorp) confirmed that the most effective doses for pilot-scale operation were the same as for full-scale treatment. After the optimization of the chemical and operational-physical parameters a SCADA (Supervisory Control and Data Acquisition) system was implemented. Two different user interfaces were provided. One was designed to operate the plant from a local terminal, located in the pilot plant laboratory. The second user interface is accessible through the World Wide Web with a web-browser. This tool makes key data like flow rate, temperature, turbidity, and pH accessible from a remote location and long-term tests can be monitored without an operator present on site. During the startup phase, turbidity, UV_{254}, and DOC removal were investigated. Turbidity of the raw water was efficiently reduced with dual media filtration to values below 0.1 NTU during continuous operation. An average DOC reduction of 50.9 % ($\sigma = 6.3$) for the coagulation / flocculation process and 49.8 % ($\sigma = 7.4$) for the whole treatment process including filtration, confirmed the similarity of the pilot-scale and full-scale unit operations. The $SUVA_{254}$ reduction indicated efficient removal of hydrophobic compounds. A mean $SUVA_{254}$ reduction of 65.7 % ($\sigma = 2.4$) for the pilot plant, with average values of 2.7 L/(mg*m) ($\sigma = 0.23$) in the filtered water, was achieved. A high oxidant demand of the raw water was determined by investigating the manganese reduction. To achieve a 50 % removal of the initial manganese concentration in raw water, a 300 % stoichiometric ratio was found to be necessary.

These findings confirm the capability of this pilot plant to simulate the turbidity, UV, and TOC removal of conventional full-scale unit operations. In combination with the SCADA system, the pilot plant proved to be a viable tool to support long-term investigations.

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CHAPTER 1

INTRODUCTION

1.1 Background

In 2001, the Colorado School of Mines and the City of Golden established a partnership to enhance hands-on experience with conventional and advanced water treatment unit operations for students. As a result, a pilot plant laboratory, located in the Golden Water Treatment Plant, was established. This pilot plant allows students to gain further insight into conventional and advanced water treatment processes. The plant will also be employed to investigate modifications on smaller scale before implementing them on full-scale treatment units on Golden's Water Treatment Plant (GWTP).

Pilot plant studies are conducted for a variety of reasons. Alternative processes may be researched and compared prior to implementation on full-scale. A thorough investigation of unit operations on pilot-scale will give detailed information about the practicability and effectiveness of alternative processes. Process optimization on a smaller scale will result in significant cost savings and provide important insight for estimating operation and maintenance costs. Several process improvements, now commonly employed on full-scale, are the result of previous successful pilot studies (Stoops 2000). For example, direct filtration, in-line mixing, shortened flocculation times, high-rate filtration, are improvements of established treatment processes, developed on pilot-scale.

Emerging contaminants, more stringent water regulations, and growing public concern make investigations on pilot-scale necessary to proof the effectiveness of current processes. The results from pilot plant studies can give regulatory agencies the confidence to approve new technologies and municipalities the confidence to employ them. Certain regulations such as the Corrosion Monitoring Regulation require long-term investigations, which are easier and less costly to apply on pilot-scale rather than on full scale (Stoops 2000).

Pilot plant studies on site also provide the advantage of using site-specific design criteria, rather than having to use generic or conservative rule-of-thumb design criteria. Seasonal fluctuations in the raw water quality and specific local conditions are easier to conduct on pilot-scale, especially when they are operated at full-scale plants.

1.2 Research Needs

The Golden Water Treatment Plant is using source water from Clear Creek, which is highly influenced by historic mining activity (estimated 1,300 abandoned mine sites, DeJong K. et al. 2003). Due to the high load of heavy metals, the entire watershed was listed for cleanup under the Federal Superfund program in 1983 (EPA 1983). Since the beginning of the cleanup project significant improvements have been established and are still ongoing. Run-off events like in April of 2003 resulted in a tremendous increase of heavy metals in Clear Creek and represented a significant challenge to the GWTP. In order to be prepared for these incidents, research is necessary to identify performance limits and adjustments to operation. This research is best conducted on pilot-scale since the same raw water can be investigated over an extended period of time. This allows one to address water quality issues due to seasonal changes as described.

Research on pilot-scale is also needed for comparison and certification of new treatment techniques as described in 1.1.

1.3 Hypothesis

Can conventional full-scale water treatment unit operations be simulated through continuous unit processes on pilot-scale?

The objectives of this study are to design and construct a conventional water treatment plant on pilot-scale, capable of simulation full-scale unit operations currently employed at GWTP. Monitoring and operation of this pilot plant should be automated, allowing continuous operation and remote-less monitoring through the World Wide Web. This study was conducted in three phases: Design, construction, and optimization of pilot-scale unit operations (Phase 1), program of SCADA (Supervisory Control and Data Acquisition) software (Phase 2) and start-up evaluation (Phase 3).

CHAPTER 2

THEORY

2.1 Regulations

The history of the latest drinking water regulations goes back to the year 1914, when the U.S. Department of Treasury promulgated drinking water standards for bacterial contamination. Since the first drinking water regulations were established, other water constituents, water quality standards and operational requirements have been added to the regulations. Although the design of a water treatment facility is governed by the existing water quality regulations, future demands have to be addressed with the proposed design criteria. Therefore sufficient flexibility to meet new and more stringent regulations need to be implemented in design requirements.

2.1.1 Safe Drinking Water Act (SDWA)

The U.S. Environmental Protection Agency (EPA), founded in 1970, published the first edition of the Safe Drinking Water Act (SDWA) in 1974 (USEPA 1974). USEPA set the Maximum Contaminant Level Goals (MCLG) for contaminants found in drinking water in 1986 and 1996 (USEPA 1986, 1996). These MCLG provide an adequate margin of safety in order to protect human health. For individual contaminants, USEPA must establish a **Maximum Contaminant Level (MCL)** that is as close to the MCLG as feasible by applying the Best Available Technology (BAT). Besides taking cost in consideration, the BAT, identified for each contaminant, must be an economically feasible technology, which is proven under field conditions.

If analytical techniques are not economically or technologically feasible to remove a given contaminant, such as virus and parasite, then the USEPA defines a treatment technique for that contaminant instead of an MCL. The treatment technique must, in USEPA judgment, be capable of providing an economically feasible way to reduce human health risks.

Besides the MCLG and MCL, the USEPA also established National Secondary Maximum Contaminant Levels (NSMCLs), which are non-enforceable goals for preserving the aesthetic qualities of drinking water. Although the secondary standards are not enforceable at the federal level, some state regulatory agencies have adopted them as additional primary standards, and therefore they are enforced at state level.

2.1.2 Stage 1 Disinfectants and Disinfection By-product Rule (Stage 1 DBPR)

In 2001 the USEPA published the Stage 1 Disinfectants and Disinfection Byproduct Rule (Stage 1 DBPR), which established seven new standards for contaminants. They include Total Trihalomethanes (TTHM), Five Haloacetic Acids (HAA5), Bromate, Chlorite (plants that use chlorine dioxide) and disinfectants like Chlorine, Chloramines and Chlorine dioxide. It also requires a treatment technique for **enhanced coagulation or enhanced softening** to reduce the Total Organic Carbon (TOC). By reducing the level of TOC, the formation of Disinfection Byproducts (DBP) will also be reduced. There are two ways to meet this requiremet. The first is to meet the percentage removal requirements of TOC based on the raw water TOC and the source water alkalinity. If a system cannot meet the percentage removal requirements of the first step, the facility has to apply to the primary agency (State level) to determine the point of diminishing returns (PODR). PODR is the point on the TOC versus coagulant dose plot, where the slope changes from greater to less than 0.3 mg/L of TOC removal for 10 mg/L coagulant dose. At this point of change, the alternative removal percentage of TOC can be set.

The Stage 1 DBPR is a revision of the Interim Surface Water Treatment Rule (IEWTR) and of the State Primary Requirements to Implement the SDWA

Amendments. It applies to all public water systems using conventional filtration regardless of size.

2.1.3 Stage 2 Disinfectants and Disinfection By-product Rule (Stage 1 DBPR)

The Stage 2 DBPR addresses the risk of trade-off between pathogens and Disinfection Byproducts (DBP). All systems must perform an Initial Distribution System Evaluation between August 2004 and August 2006, to locate DBP hot spots. Stage 2 MCLs for TTHMs and HAA5 will stay the same as in Stage 1 DBPR. A Locational Running Annual Average (LRAA) regulates the limits for each monitoring site.

2.1.4 Surface Water Treatment Rule (SWTR)

Under the SWTR, all public water systems using surface water or groundwater under the direct influence of surface water must **disinfect**, and may be required to filter, unless certain source water requirements and site-specific conditions are met. Treatment technique requirements are established instead of MCLs for Giardia lamblia, viruses, heterotrophic plate count bacteria, Legionella and turbidity.

The applied treatment process must reliably achieve at least a 3-log (99.9 %) removal and/or inactivation of Giardia lamblia cysts and a 4-log (99.99 %) removal and/or inactivation of viruses. This requirement has to be met between the watershed and a downstream point prior to deliver to the first customer. The adequacy of the filtration process is determined by measuring turbidity in the treated water. USEPA sets performance requirements, which depend on the installed filtration method.

2.1.5 Interim Enhanced Surface Water Treatment Rule (IESWTR)

The IESWTR regulates microbial contaminants, particularly cryptosporidium, by defining turbidity performance standards for surface water and groundwater systems under surface water influence that serve 10,000 customers and more. These systems must prove a turbidity level, of 0.3 NTU or less in at least 95 percent of measurements, taken each month. If the system meets these turbidity requirements, it is assumed to achieve the required 2-log (99%) cryptosporidium removal. Additionally, a minimum disinfectant residual above 0.2 mg/l entering the distribution systems is required for all systems.

2.1.6 Long-term Enhanced Surface Water Treatment Rule (LT2ESWTR)

The LT2ESWTR was developed simultaneously with the Stage 2 Disinfectants and Disinfection By-product Rule and focuses on filtration provisions and microbial protection. Within this rule all systems will be categorized into one of four “bin” classifications, based on the raw water quality. The source water monitoring has to be accomplished between January 2005 and January 2007. Systems having poor raw water quality will be required to add additional log removal credits, which can be achieved via numerous non-treatment and treatment techniques.

2.1.7 Pending Regulations

Several new regulations for radionuclides, sulfate, and methyl-t-butylether are summarized in Table 2.1.

Table 2.1: Pending Regulations

Regulation	**Proposed Rule by:** **Final Rule by:**
Radionuclides (Radium, Uranium, Alpha, Beta and Photon Emitters)	Final Rule for Radionuclides by November 2000, Final Rule for Uranium by 2000
Sulfate	August 6, 2000 (Determination to regulate)
Methyl tertiary butyl ether (MTBE)	No schedule

2.1.8 Colorado Primary Drinking Water Regulations (Colorado PDWRs)

Pursuant to the federal SDWA and corresponding state legislations, the Colorado Department of Public Health has established the Colorado Primary Drinking Water Regulations (Colorado Department of Public Health & Environment 2002). The Colorado PDWRs and amendments are applied to all public water systems in the State of Colorado and include the SDWA, Stage 1 DBPR, SWTR, and further pending regulations.

2.2 Elements of a drinking water treatment plant

Besides drinking water regulations, design criteria have to address public concerns, increasing water demands, and potential future quality changes in the water source. In order to address these needs, a thorough understanding of the treatment processes proposed is inevitable.

The following description focuses primarily on conventional unit operations to treat surface water, in order to meet drinking water standards. The description considers the treatment plant of Golden’s Water Treatment Plant, a surface water plant with a capacity of 12 mgd (million gallons per day). The water is mainly treated with conventional treatment processes, including pre-oxidation, coagulation, flocculation, sedimentation, filtration, and disinfection.

2.2.1 General / Overview of Golden Water Treatment Plant

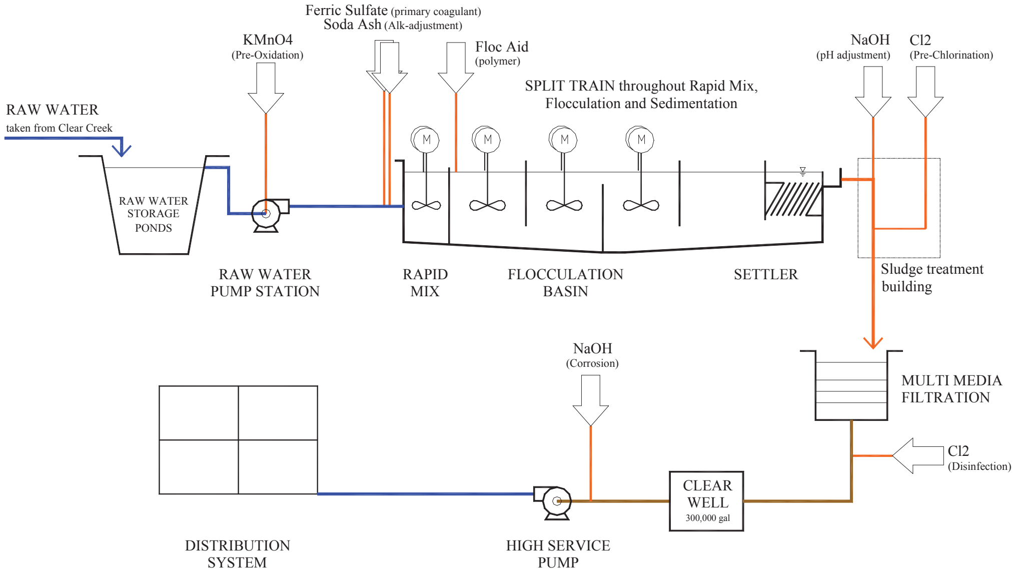


Figure 2.1: Schematic Golden Water Treatment Plant (GWTP)

The GWTP (Figure 2.1) is designed to treat surface water with a capacity of twelve mgd. The water is taken out of Clear Creek and stored in two holding ponds before being treated. The holding ponds act as a backup and provide time for sand and debris to settle out, before the water reaches the plant. The GWTP includes a pre-oxidation step with potassium permanganate ($KMnO_4$), which oxidizes manganese, iron, and organic and metallic compounds. $KMnO_4$ is added at the raw water pump station, which gives the chemical enough retention time (approximately 30 sec at low flow conditions) to react with the raw water. Ferric Sulfate ($Fe_2(SO_4)_3*9H_2O$) as a primary coagulant and usually lime for alkalinity adjustment are added prior to the rapid mix chamber. For enhanced flocculation a non-ionic polymer (Nalco 8181) is added at the first stage of flocculation. A fast stirring mixer in the rapid mix chamber accomplishes a thorough dispersion of the added chemicals and the water. The rapid mix chamber, flocculation and sedimentation basin, and the plate settler are designed as a split train, which greatly facilitates operational changes. Full-scale assessment of treatment options can be achieved in one train, without influencing the other. After the water passes the split train, caustic soda (NaOH) is added inline to raise the pH. This is also the point where chlorine (Cl_2) is added for chlorination prior to the filters. The following filters are operated as multi-layer filters with anthracite, sand, garnet, silica-gravel and clay tiles. Finally chlorine is added for disinfecting purposes. After passing through the clear well, caustic soda (NaOH) is added for corrosion control.

2.2.2 Pre-Oxidation ($KMnO_4$)

The Golden Water Treatment Plant has to deal with unusually high manganese concentration, which originates from the historic mining activities in the watershed (DeJong K. et al. 2003). Because of the elevated manganese levels in the influent water, Mn^{2+} removal is a priority for the Golden Water Treatment Plant.

Since there are no known health risks associated with manganese, the EPA is regulating manganese by setting a secondary drinking water standard for aesthetic reasons. The secondary maximum contaminant level (SMCL) for manganese in 2003 is 0.05 mg/L.

The GWTP accomplishes the Mn treatment with a pre-oxidation step, where potassium permanganate ($KMnO_4$) is added to the water before the rapid mix is reached.

2.2.2.1 Manganese chemistry

Manganese can occur in seven different oxidation stages, whereas Mn^{2+}, $MnO_2(s)$ and MnO^{4-} are stable over a wide pH-E range (Figure 2.3, Samuel and Osman 1999). In general, the occurrence of several Mn-forms in the source water is largely dependent on biological activity. According to the natural cycle, oxidizing and reducing bacteria are responsible for the occurrence of dissolved (Mn^{2+}) and solid (MnO_2) manganese in water (Figure 2.2), which correlates with the dissolved oxygen level.

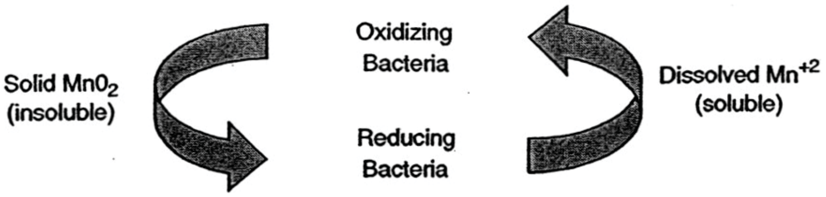


Figure 2.2: Manganese biochemical cycle (Carlson et al. 1997)

If there is enough oxygen available, the oxidizing bacteria dominate and more $MnO_2(s)$ is built. With lower pH ranges, where reducing conditions are encouraged (Figure 2.3), a higher DOC level slows down the Mn-oxidation process, because of interference from certain organic acids (with one or more carboxylic acid groups) (Sommerfeld 1999).

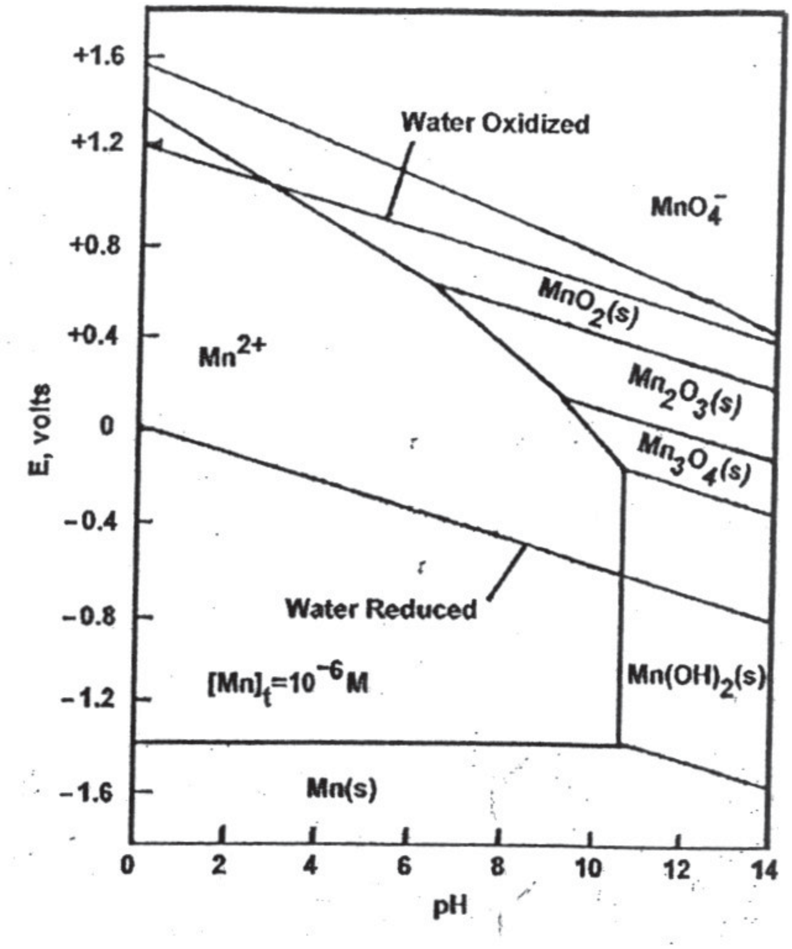


Figure 2.3: E-pH stability diagram for manganese-water at 25°C (Samuel and Osman 1999)

2.2.2.2 Oxidation theory

The effectiveness of an oxidant to convert Mn^{2+} into MnO_2 depends on the total oxidant demand, the temperature, the pH-E range, alkalinity, and the presence of competitive oxidizing species. The oxidizing process occurs in three different steps (equation 2.1, 2.2, 2.3):

$Mn^{2+} + \frac{1}{2}O_2 \rightarrow MnO_2(s)$ (slow) (2.1)

$Mn^{2+} + MnO_2(s) \rightarrow Mn^{2+}*MnO_2$ (fast) (2.2)

$Mn^{2+}*MnO_2 + \frac{1}{2}O_2 \rightarrow 2MnO_2(s)$ (very slow) (2.3)

Depending on the chosen oxidant a distinct stoichiometric ratio is necessary for complete oxidation. In theory, for 1 mg Mn^{2+}, 1.92mg of $KMnO_4$ as an oxidant (equation 2.4) are required. This ratio does not address the demand of other constituents (organic acids containing one or more carboxylic acid groups, Sommerfeld 1999) in the water. Therefore a higher oxidant concentration is necessary for effective manganese oxidation.

$$3Mn^{2+} + 2KMnO_4 + 2H_2O \rightarrow 5MnO_2(s) + 2K^+ + 4H^+ \qquad (2.4)$$

The efficiency of the removal mechanism is related to the initial Mn^{2+} concentration. More Mn-oxidation occurs when the initial concentration is higher. Gregory and Carlson (2001a) reported the lowest Mn^{2+} concentration in treated water (<10 µg/L) when the initial Mn^{2+} concentrations were the highest (1000 µg/L). Also the kinetic of the Mn^{2+}-oxidation is affected by the initial Mn^{2+} concentration. The higher the Mn^{2+} concentration in the source water the faster the reaction occurred (Gregory and Carlson, 2003). Further more, the presence of DOC (dissolved organic carbon) decreased the rate of Mn^{2+} oxidation.

2.2.3 Coagulation

2.2.3.1 Treated water constituents

Coagulation is also defined as the chemical conditioning of **colloids** (Qasim et al. 2000), which are suspended particles at the lower range of the particle size spectrum, from 0.001 µm to 1 µm. Colloids include inorganic particles and organic particles like humic substances, viruses, bacteria or plankton. Depending on their affinity to water they can be either hydrophobic or hydrophilic (Reynolds and Richards 1996).

Colloids have a very large surface area to mass ratio. Their mass is so small that gravity has little effect on their settling behavior. Beside gravitational forces three other mechanisms control the behavior of colloids: Electrostatic forces, van der Waals forces, and Brownian motion.

Electrostatic forces**:** Most colloids are electrically charged, like metallic oxides, which are positively charged. Metallic sulfides and nonmetallic oxides are negatively charged. In general, the negative charge dominates in natural water (Niehof and Loeb 1072; Hunter and Liss 1979). This surface charge attracts other ions, the counter-ions**,** to bind on the surface of colloids, and they form a double layer around the colloid. Close to the surface of the colloids, protons and cations in general, form the stern layer. Because of their asymmetric charge, also water molecules are attached to the surface of charged particles. The next layer is called the diffused layer, which contains ions of both electrical charge, but the majority is of opposite charge (counter-ions). The water molecules build a shear surface. Inside this shear surface they behave as attached to the colloid and outside they behave as independent molecules. The electrical charge on the shear surface is called the zeta potential and gives an indication of the stability of the colloidal system and the effectiveness of the coagulation process.

Van der Waals forces**:** A force of attraction exists between any two masses. The magnitude of this attraction is a function of the mass and distance between two masses. The van der Waals forces act as the antithesis of repulsive energy, which is based on electrostatic forces (Figure 2.4).

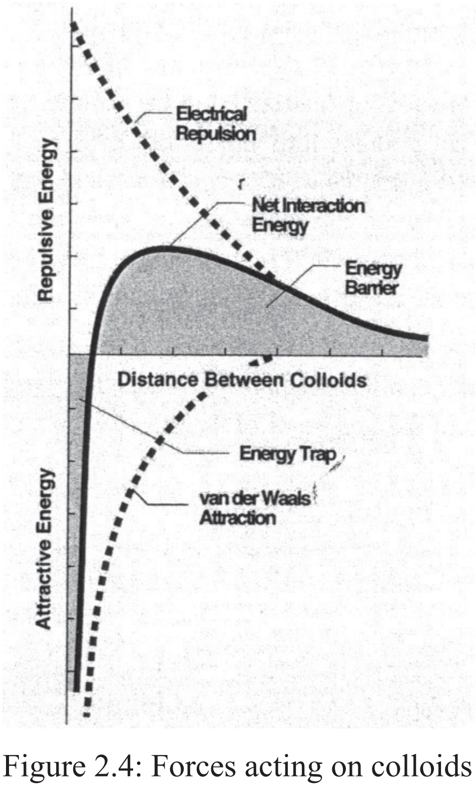


Figure 2.4: Forces acting on colloids (Ravina 1988)

Brownian Motion describes the phenomenon of collisions between molecular size particles. The water temperature is the main driving-force for this random movement (Montgomery 1985). The influence of the Brownian motion in the coagulation process is insignificant.

2.2.3.2 Principle of Coagulation

During the process of coagulation, metal salts (aluminum sulfate, ferric sulfate, ferric chloride or ferrous sulfate), which are added to water, will hydrolyze into complex metal hydroxides ($Me_x(OH)_y$). This reaction depends on the pH and the coagulant dosage (Figure 2.5).

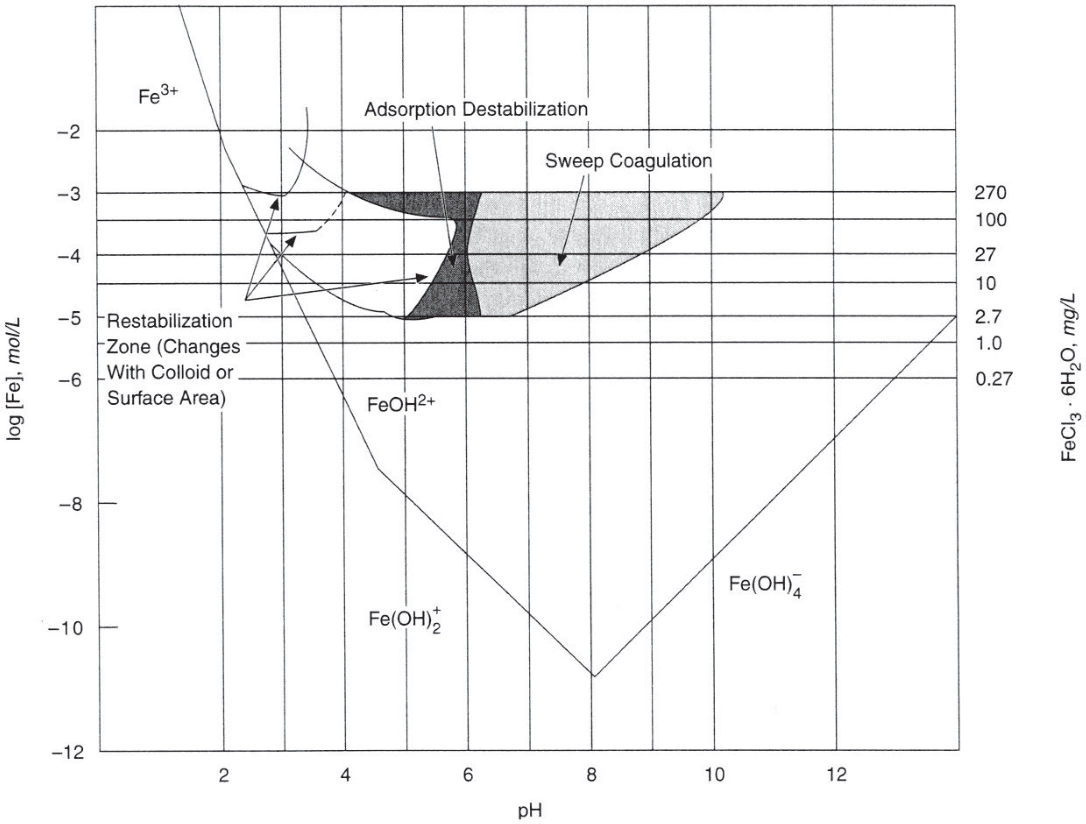


Figure 2.5: Equilibrium solubility domain of ferric hydroxide in water. Shaded area shows range of water treatment process (Chapman 1998)

Coagulation typically destabilizes the colloids by five different mechanisms: compression of the double layer, counter-ion adsorption and charge neutralization, interparticle bridging, enmeshment in a precipitate, and heterocoagulation (Qasim et al. 2000).

Compression of the double layer (DLVO theory): By adding a positively charged coagulant, the concentration of the counter-ions in solution increases, the net charge in the diffused layer neutralizes, and the layer compresses. Finally, van der Waals forces predominate and the colloids agglomerate into a floc (Figure 2.6).

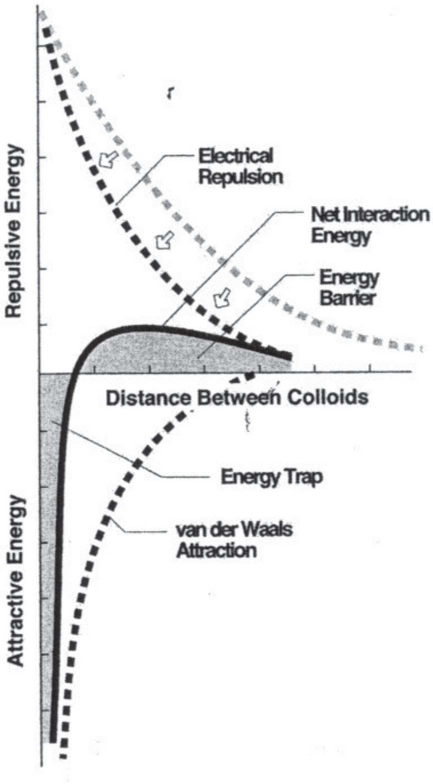


Figure 2.6: Forces acting on a colloid after compression of the double layer (Ravina 1988)

Counter-ions adsorption and charge neutralization: Counter-ions from the coagulant adsorb onto the surface of the colloids and finally the repulsive charge on the surface of the particles is neutralized. These destabilized colloids can adhere to each other to form colloidal-colloidal complexes, driven by van der Waals attraction or further adsorption of counter-ions. Excess addition of a coagulant may result in restabilization of the destabilized particles by charge reversal. Furthermore, the net charge can be reversed by adsorption of counter-ions (Qasim et al. 2000).

Interparticle bridging: Besides the coagulant, high molecular weight synthetic organic compounds, called polymers are added at the coagulation step. These polymers have a strong tendency to adsorb on the surfaces of most particles in an aqueous system and improve the treatment efficiency. The interparticle bridging starts with adsorption of the polymer onto specific surface sites of colloidal and/or coagulant particles. As a result, particle-polymer-particle aggregates are formed and the polymer acts as a bridge. Excess dosages of polymer cause re-stabilization due to surface saturation or sterical stabilization.

Enmeshment in a precipitate (sweep floc coagulation): Metal salts hydrolyze and form $Me_x(OH)_y$, which are extremely insoluble in water and therefore precipitate out and form accumulates. Colloidal particles are enmeshed in the hydroxide floc structure, which is termed sweep floc coagulation.

Heterocoagulation: The charge on the surface of some naturally occurring particles may not be uniform. Heterocoagulation is known as the coagulation, which occurs via simple electrostatic interaction between opposite charged sides of a particle.

Several regulations (IEWSTR, Stage 1 DBPR) require enhanced coagulation processes. In general, enhanced coagulation is the addition of excess coagulant dosage for improved removal of total organic carbon (TOC) (Stage 1 DBPR) and Natural Organic Matter (NOM), color, arsenic and other heavy metals. Aside from the described coagulation mechanisms, precipitation and adsorption play an additional role (Qasim et al. 2000).

Precipitation of natural organic matter refers to the formation of an aluminum or iron humate or fulvate with a low solubility product (Qasim et al. 2000).

From the known adsorption phenomena for coagulation, co-precipitation is the most important process, involved in enhanced coagulation. From all the known surface functional groups, only the surface hydroxyl group (i.e. $\equiv$S-OH) is the reactive and exchangeable site, where adsorption occurs. The soluble organic material, which adsorbs onto the reactive sites on the surfaces of growing hydrous metal oxide crystals, is termed surface complex formation. The most important factors influencing this phenomenon are: site specifity, the pH dependency and the surface of the hydrous metal oxides (Letterman at al. 1999).

2.2.3.3 Unit Operation

Addition of chemicals for coagulation and precipitation requires a rapid and thorough mixing. This mixing process is known as rapid mix. Rapid mix can be accomplished with an impeller to create turbulence in the mixing chamber. This is classified as mechanical mixing. Static mixing uses hydraulic jumps or turbulent flow in a pipeline to create turbulence, which thorough disperses the added chemicals with the water (Qasim et al. 2000).

2.2.4 Flocculation

The flocculation process promotes the interaction of particles and the formation of aggregates that can be removed efficiently in subsequent separation processes. Efficient mixing, expressed through the velocity gradient (G value) is the basis for effective flocculation. Several physical mechanisms are responsible for the growth of the flocs from the coagulated water. These mechanisms are divided in parakinetic and orthokinetic forces. The parakinetic forces describe the interparticle contacts via Brownian motion. Within the orthokinetic forces, usually the predominant mechanism, the fluid motion is responsible for the interparticle contact.

Flocculation takes place in a basin, where the mixing is achieved via hydraulic or mechanical mixing. The hydraulic flocculators simply utilize cross-flow baffles to produce the required turbulence. Mechanical flocculators, where the mixing is achieved with stirrers are more common. Typically horizontal-shaft paddle-wheel mixers are used.

2.2.5 Sedimentation

Sedimentation is a physical treatment process that utilizes gravity to separate suspended solids from water. The settling process is classified into four different categories: discrete settling, flocculant settling, hindered settling (zone settling), and compression settling**.** The discrete settling describes the sedimentation of particles of low concentration with unhindered settling at a constant velocity. The settling theory is based on Newton's Law and describes the forces acting on a particle as the gravitational and the drag forces (Figure 2.7).

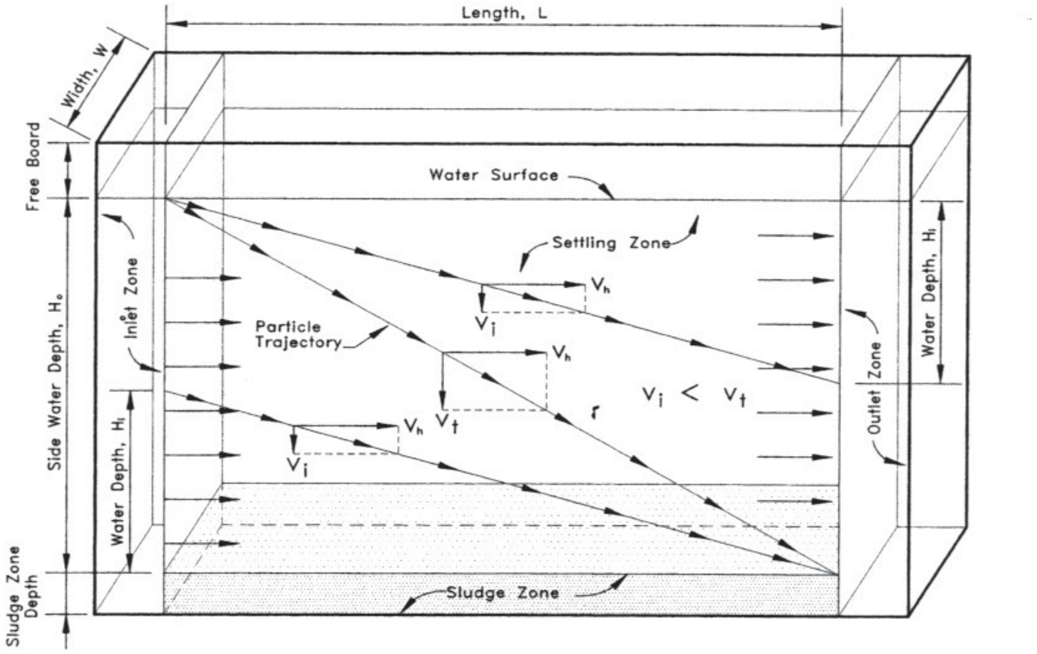
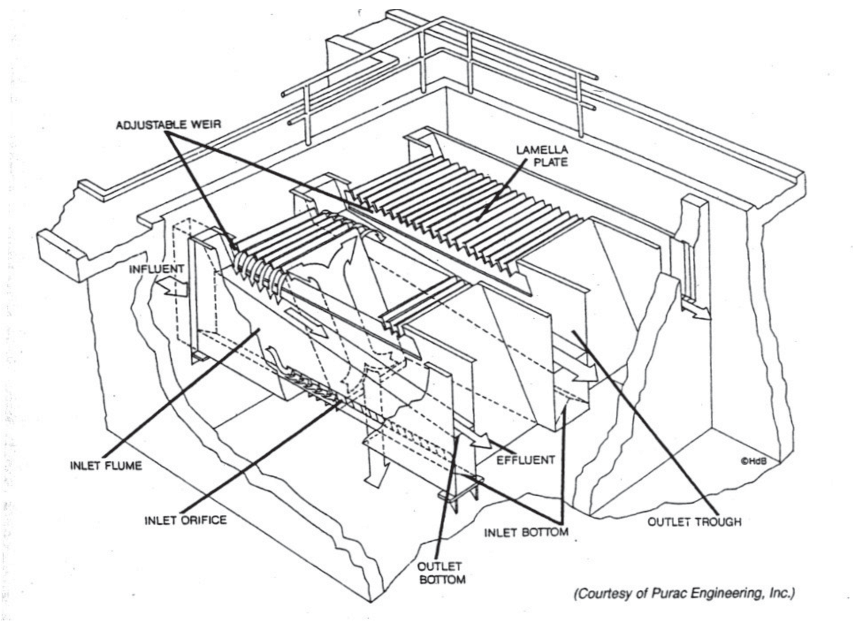


Figure 2.7: Forces on a settling particle (Qasim et al. 2000)

The flocculant settling differs from discrete settling because agglomeration of particles occurs. The particle concentration is high enough to ensure particle collision and the physical properties cause them to coalesce. This particles start to settle out as discrete particles, but settle down faster as soon as agglomeration occurs. This sedimentation process is more complicated. No mathematical model has yet been developed and further research is necessary. Hindered and compression settling apply to gravity sludge thickeners in water treatment (Qasim et al. 2000).

Short-circuiting is a common problem in full-scale sedimentation basins and reduces the actual detention time compared to the calculated detention time (Gregory et al. 1999). The efficiency of particle settling in horizontal flow depends on the area available for settling. To increase the area, laminar-flow devices are installed. These devices consist of banks of small square tubes or plates, which are installed near the outlet of the basin (Figure 2.8).



(Courtesy of Purac Engineering, Inc.)

Figure 2.8: Technical drawing of a plate settler / sed basin outlet (Willis 1990)

2.2.6 Filtration

The filtration step in a water treatment plant guarantees further removal of colloidal particles. Straining, Sedimentation, Impaction and Interception are the four simultaneously acting mechanisms involved in the filtration process (Qasim et al. 2000).

Straining describes the mechanism for particles, which are too large to pass through pore spaces. These particles become trapped and are removed from the filter influent. Straining plays an important role in the direct filtration process, where flocculated water is directly fed to the filters. Sedimentation occurs in low-velocity zones in the filter bed. Impaction: When particle mass is too large to follow sharp turns in the flow-streamline, these particles strike the medium and stay outside the flow-streamline, because their inertia is greater than the hydrodynamic force. Interception: Particles may partly follow a streamline and will be lodged on a media grain as soon as they touch it.

The physical and chemical properties, which further contribute to removal mechanisms, are chemical bonding between media and particles, physical attraction between media and particles, and physical/chemical attraction between particle and particle (Tchobanoglous and Schroeder 1985).

The fluid motion through annular spaces between media grains is described as orthokinetic flocculation. It increases the number of interparticle contacts and results in larger particles than the original individual particles. Removal through one of the mechanisms described above will take place.

Longer operations of filter media will increase the straining action, the velocity of the water running through the pore spaces, the shear forces and the head loss. This results in a decrease of the filter rate, the filter performance and efficiency and is described as filter bed clogging. A filter backwash on a regular basis is necessary.

Reverse gradation (stratification) occurs when larger grains settle out faster then smaller grains. This is why just the top of a filter bed traps most of the particles. This problem occurs in operating single media filters and is solved by installing dual media filters where anthracite coal is the upper layer and quartz sand is on the bottom (Figure 2.9). A dual media filter behaves like two single media filters in series.

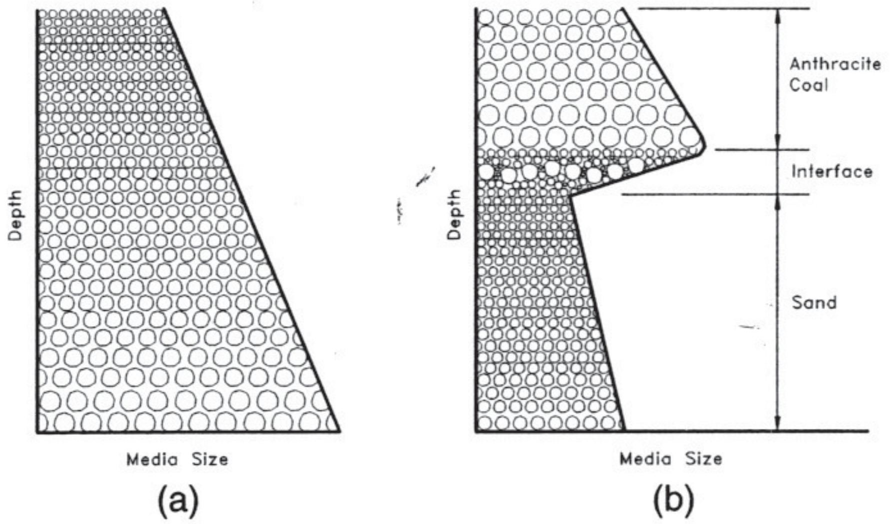


Figure 2.9: Gradiation versus depth for (a) single medium filter (b) dual media filter (Qasim et al. 2000)

Filter types commonly utilized in water treatment are classified based on the filtration rate, driving force, and the direction of flow.

2.2.7 Disinfection

Disinfection is a required treatment process (SWTR, EWSTR) for inactivation of organisms, which are capable of causing diseases. These pathogens occur in surface and groundwater (Qasim et al. 2000). Several opportunities exist to disinfect the treated water before it reaches the distribution system. The GWTP uses chlorine as a disinfectant, like the majority of the water treatment plants in the United States (Qasim et al. 2000). Chlorine can be applied to the system in various forms. Chlorine gas, which is an effective oxidizer, hydrolyzes when dissolved in water and forms hydrochlorous acid (HOCl, equation 2.5), whereas HOCl is a weak acid.

$$Cl_2 + H_2O = HOCl + H^+ + Cl^- \qquad (2.5)$$

In this form, chlorine exists as free chlorine residual and undergoes a partial dissociation reaction (equation 2.6), where the relative concentration of hydrochlorous acid (HOCl) is a function of pH, temperature, and the chlorine concentration in solution is (Figure 2.10).

$HOCl \leftrightarrow H^+ + OCl^-$ (2.6)

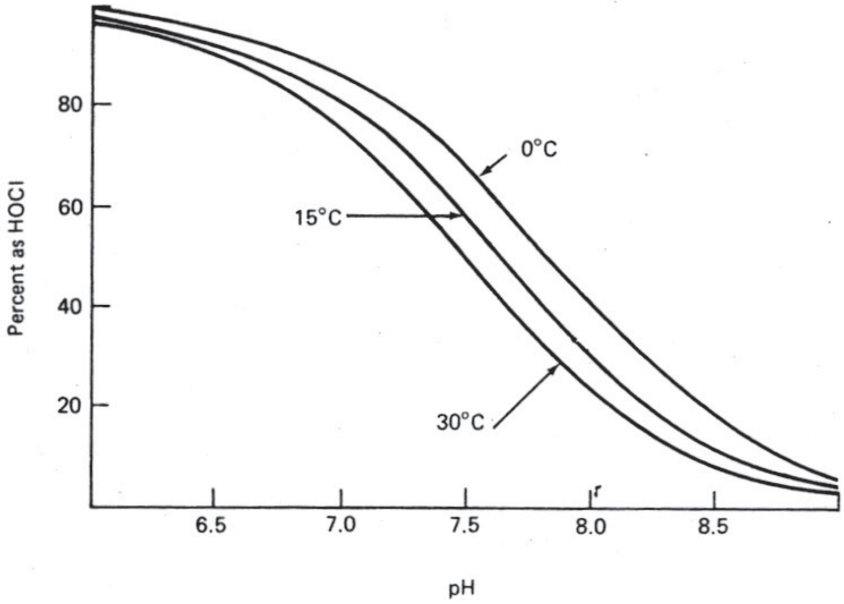


Figure 2.10: Relative $HOCl/OCl^-$ concentration shown over the pH range (Hesby 2000)

HOCl, which has an oxidation potential of 1.49V, is nearly 1000 times stronger oxidant than OCl^- (Hesby 2000) and it is predominant at pH ranges below 6.

Also, chlorine can be added to the water in the form of calcium hypochlorite ($Ca(OCl)_2$) or sodium hypochlorite (NaOCl), but both will raise the pH (equations 2.7, 2.8).

$Ca(OCl)_2 + 2H_2O = 2HOCl + Ca^{2+} + 2OH^-$ (2.7)

$NaOCl + H_2O = HOCl + Na^+ + OH^-$ (2.8)

The necessary chlorine concentration is dependent on the initial chlorine demand, the combined chlorine residuals and the free chlorine residuals (Figure

2.11). The maintenance of free chlorine residuals is the principal means by which water utilities ensure that the water they provide is properly disinfected.

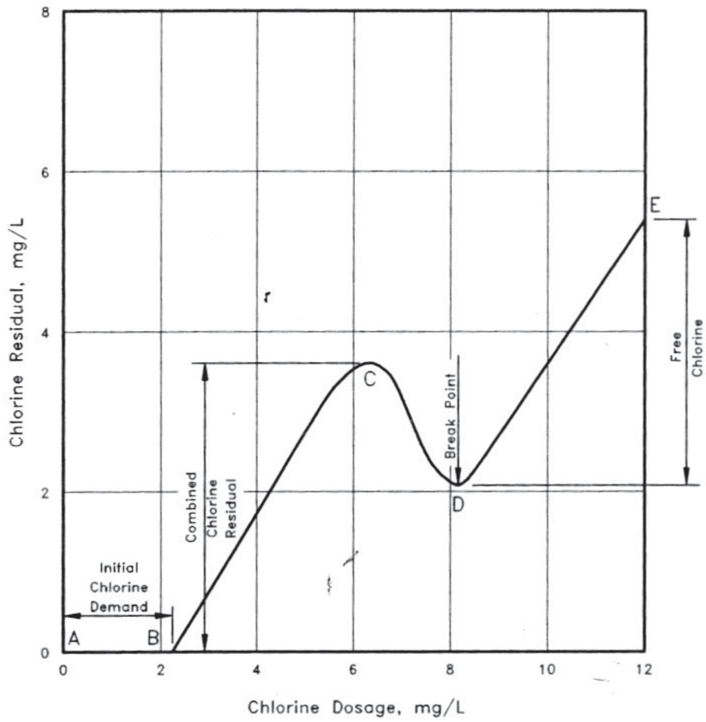


Figure 2.11: Typical chlorine residual curve (Qasim et al. 2000)

The initial chlorine demand is the chlorine concentration, necessary to react with NOM in the water. The reaction of HOCl with ammonia forms combined chlorine residuals (equations 2.9, 2.10, 2.11) in the form of chloramines.

$$NH_3 + HOCl \rightarrow NH_2Cl + H_2O \qquad (2.9)$$

$$NH_2Cl + HOCl \rightarrow NHCl_2 + H_2O \qquad (2.10)$$

$$NHCl_2 + HOCl \rightarrow NCl_3 + H_2O \qquad (2.11)$$

Chloramines are weak disinfectants, but provide a stable residual in the distribution system. As soon as the ammonia constituents are exhausted further addition of chlorine causes a decrease in combined residual. After the breakpoint chlorination the chloramines are oxidized to oxides, nitrogen, other gases, and free chlorine residuals develop (Qasim et al. 2000). Aside from mono-, di- and tri-chloramine, nitrogen and nitrate are also formed. At a recommended Cl_2/NH_3

weight ratio of 9 mg Cl_2 / mg NH_3 (Hesby 2000) mainly mono-, dichloramine and nitrogen are formed (Table 2.2).

Table 2.2: Chlorine dose required for ammonia-chlorine reaction (Hesby 2000)

Reaction	mg Cl_2 / mg NH_3
Monochloramine (NH_2Cl)	4.2
Dichloramine ($NHCl_2$)	8.4
Trichloramine (NCl_3)	12.5
Nitrogen (N_2)	6.3
Nitrate (NO_3)	16.7
Recommended design dose for free residual reaction	9

2.3 Basic Design Criteria

Selecting the appropriate equipment to treat water requires a thorough understanding of the unit operations involved, especially the process mechanism, the necessary equipment and the material of construction. A thorough assessment of the purpose of a pilot-study is a necessary step before a pilot-plant can be designed. The most important decision in designing a pilot-plant is to determine which variables will be studied and what their characteristics should be. A data-assessment, the data collection methods, and interpretation is required before the equipment can be chosen.

2.3.1 General

In general a pilot-plant design should be kept as simple and flexible as possible. A modular configuration should be conducted rather than a ‘one-unit’ pilot-plant design. Besides being more flexible for future pilot-studies, this approach has several advantages for transport and maintenance. The arrangement and selection of the proposed pilot-plant modules should follow the unit operations of the full-scale plant. The design should begin with the primary process of interest. If the pilot-study focuses on filtration, the filtration unit should be designed first. The necessary pre-treatment steps are designed for the main module in order to provide the main process with an influent stream that meets the necessary characteristic.

Principle issues, which must be addressed early in the pilot-plant design, are various hydraulic and electrical considerations. The sample location of the source water and how the water will be delivered have to be defined. If possible, pumping the water to and through the pilot-plant should be avoided. Forcing the water through pumps could change its characteristics as compared to a full-scale plant, which in most cases is fed and operated by gravity.

The chosen equipment should be reusable, reliable and flexible. Also operation considerations should be included in the equipment selection. Therefore, energy consumption, manpower requirements, and the cost of maintenance need to be addressed.

Costs, scaling limitation and data collection are considerations, which should be taken into account by choosing an appropriate size of the pilot-plant. The conservative approach proposes bench scale tests to determine the proper size for each unit operation, whereas down-scaling of existing full-scale facilities is limited by a process-specific down-scale ratio between full-scale and pilot-scale. The size of a pilot-plant also limits the range of parameters that can be evaluated. In most cases the maximum down-scale ratio is based on experiments, and if exceeded the pilot-plant is no longer simulating the full-scale process.

In general pilot testing can be applied after optimizing each unit operation. This includes chemical optimization, the optimization of operational-physical parameters and hydraulic conditions.

2.3.2 Influent module / Source water / Pretreatment

The influent module regulates the raw water flow to the pilot plant and has to guarantee a constant hydraulic gradeline. Depending on the desired pilot study the applied raw water quality should be kept as constant as possible. In order to simulate a whole treatment period through a pilot-study, average and peak raw water qualities should be addressed. Therefore the influent module should be capable of handling more than one water source. The raw water quality should be permanently monitored, either manual or through a SCADA (Supervisory Control and Data Acquisition) system.

2.3.3 Coagulation / Flocculation / Sedimentation

The main requirement for these treatment processes is effective dispersion and mixing of any added chemical.

To design the flocculation module, the most important factors are as follows: type of the subsequent treatment process, the raw water characteristic, added chemicals, and local conditions. Taking these factors into account, several design criteria such as energy input (G-value), retention time, and type of flocculator are derived.

In order to address the chemical optimization of the coagulation and flocculation process several pilot studies recommend starting the evaluation process with the strongest coagulant (Kawamura 1982). In order to address the hydraulic optimization of the flocculation module, the time it takes the water to flow directly from the inlet to the outlet (shortcut) should be reduced to a minimum. This can be achieved by modifying the design of the flocculation basin. To discover these shortcuts, a hydraulic scale model is a useful tool. With such a model the hydraulic behavior of a designed module can be predicted. Defining this hydraulic scale model is a time intensive procedure and therefore is not practical for most pilot-studies. Constructional considerations such as separate rectangular mixing chambers or additional installed baffles cause turbulent mixing and reduce shortcutting to a minimum. Between each chamber it should be aimed for a laminar flow through pipes. In order to optimize the flocculation process, one should find an optimum combination of energy input and mixing time. The magnitude of energy input for the mixing process is defined through the velocity gradient (G-value, equation 2.13). Several pilot-studies propose a G-value between 10 and 80 s^{-1} as the most effective (Stoops 2000).

Studies of the sedimentation process in pilot-scale show that the most sedimentation occurs after a stable sludge blanket is formed. This makes a permanent operation over a longer period of time necessary. It turnes out that an inclined inlet flow provides turbulence in the sludge storage area, which promotes the formation of a sludge blanket (Lang 1982). By defining the appropriate size of tubes or plates for a defined flow a safety factor between 1.5 up to 2 show be included in the calculation (Kawamura 1982).

2.3.4 Filtration

A filter on the pilot-scale should reflect the filtration rate and the vertical dimension of a full-scale filter (Hudson 1982). The main difference of the pilot-scale filter, when compared to full-scale, is the surface area. A minimum ratio between the diameter of filter column and the filter media diameter of 50:1 is recommended to minimize the wall effects (Lang 1982). Like on the full-scale, the filtration rate should be designed to achieve a flow between laminar and the transition zone to turbulent flow (Hudon 1982). A filter diameter between 4 inch (10 cm) and 6 inch (15 cm) for gravity filter operations is therefore most common (Stoops 2000). Also the backwash procedure has to be considered in the size evaluation. When using too small filter columns, bridging can occur and the filter media could rise as a solid piston. To study backwashing behavior of a filter a much larger surface area must be applied. A minimum filter diameter of two feet is recommended (Stoops 2000).

2.4 Scaling aspects

In order to simulate established processes on a smaller scale, a thorough understanding of principle scaling aspects is necessary. Scaling is limited by physical and chemical limits. By designing a pilot-plant, chemical limitation plays a minor role. This discussion is therefore focused on physical scaling limitation.

Scaling in the context of physical problems touch the fundamentals of the model theory, which is based on dimensional analysis.

2.4.1 Dimensional analysis

The dimensional analysis is based on the fundamental statement that a mathematical description of a physico-technological problem can be only universally valid, if the problem is formulated dimensionally homogenous (Zlokarnik 2001). A dimension is a purely qualitative description of a physical entity or a natural condition like length, time or mass, which can be short, long, or either heavy or light. A physical quantity on the other hand represents a quantitative description of a physical property. It consists of a measuring unit and a numerical value like a mass of 5 pounds. Physical quantities are subdivided into primary (base) quantities and secondary quantities, which are derived through physical laws from the primary quantities. The primary quantities are based on standards and are quantified by comparison with them. Throughout the International System of Units seven base quantities are defined (length, mass, time, temperature, amount of substance, electric current strength and luminous intensity, “Systéme International d’unités”, SI).

The aim of dimensional analysis is to check, if and how the physical content in examination can be expressed in a dimensionally homogenous manner. Two steps are necessary to meet this requirement. First of all, the necessary physical parameters, which describe the problem, must be listed in a relevance-list (Zlokarnik 1991). This relevance-list contains one target quantity, which is the only dependent variable, and a comprehensive list of all affecting quantities. These affecting quantities must be primarily independent. In a second step, converting it to a dimensionless form checks the dimensional homogeneity of a physical content.

In this context the pi-theorem plays a fundamental role. The pi-theorem describes the number of independent dimensionless groups (m, equation 2.12) by reducing the amount of influence-quantities (n) with the number of basic quantities (r) (Van Deemter 1982).

$$m = n - r \tag{2.12}$$

Zlokarnik (1991, 2001) follows this theorem by preparing a dimensionless matrix. This is a unique and practical approach to solve scaling problems with the help of dimensional analysis. If the physics of a specific problem are unknown, the conservative approach has to be chosen (Pawlowski in Zlokrnik 2001), where the combination of corresponding physical laws derives dimensionless numbers, which serve as coefficients.

2.4.2 Model theory and scaling

Reliable scaling of a physico-technological problem requires a dimensionless description of a process. The only way to achieve this, is through dimensional analysis (Zlokarnik 1991). The model theory states that two processes are considered as completely similar, if they take place in geometrically similar environments, and if all dimensionless numbers, describing the process, have the same value.

2.4.3 Scaling aspects applied to mixing processes

Drinking water unit operations like rapid mix and flocculation are based on a thorough, sufficient mixing process. Traditionally, the degree of agitation in a mixing unit is measured by velocity gradient (Qasim, Motley, and Zhu 2000), which is a function of the mixing power, the volume, and the viscosity of the fluid (equation 2.13).

$G = \sqrt{(P / (V * \mu))}$ (2.13)

Following Zlokarnik's approach, the Newton-number (equation 2.14) and the Reynolds-number (equation 2.15) describe the mixing power of a stirrer (Figure 2.12).

$Ne = P / (\rho * n^3 * d^5)$ Newton number (2.14)

$Re = (n * d) / \nu$ Reynolds number (2.15)

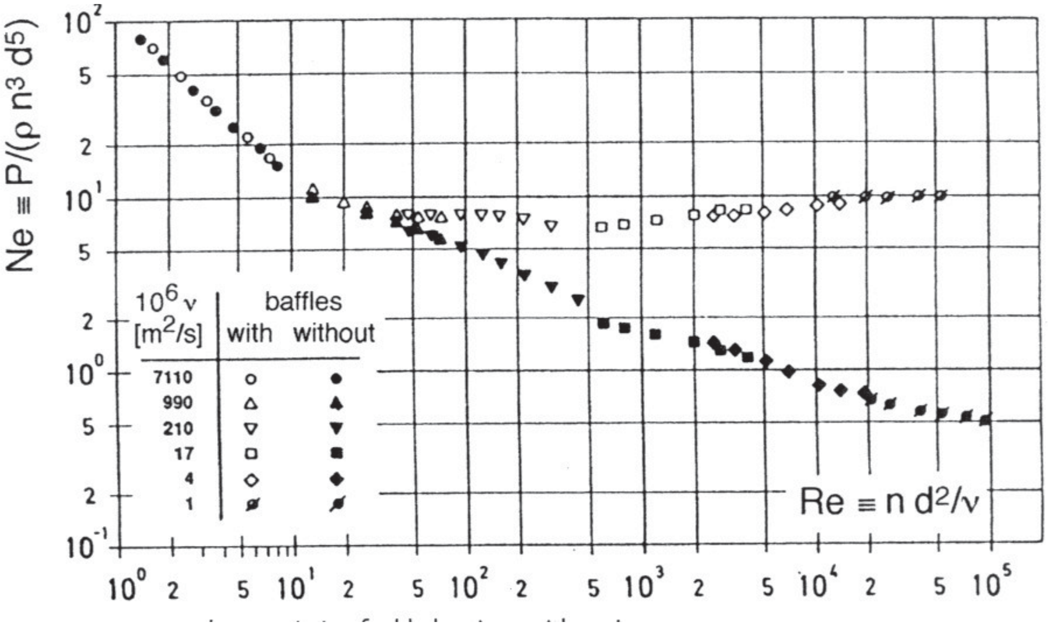
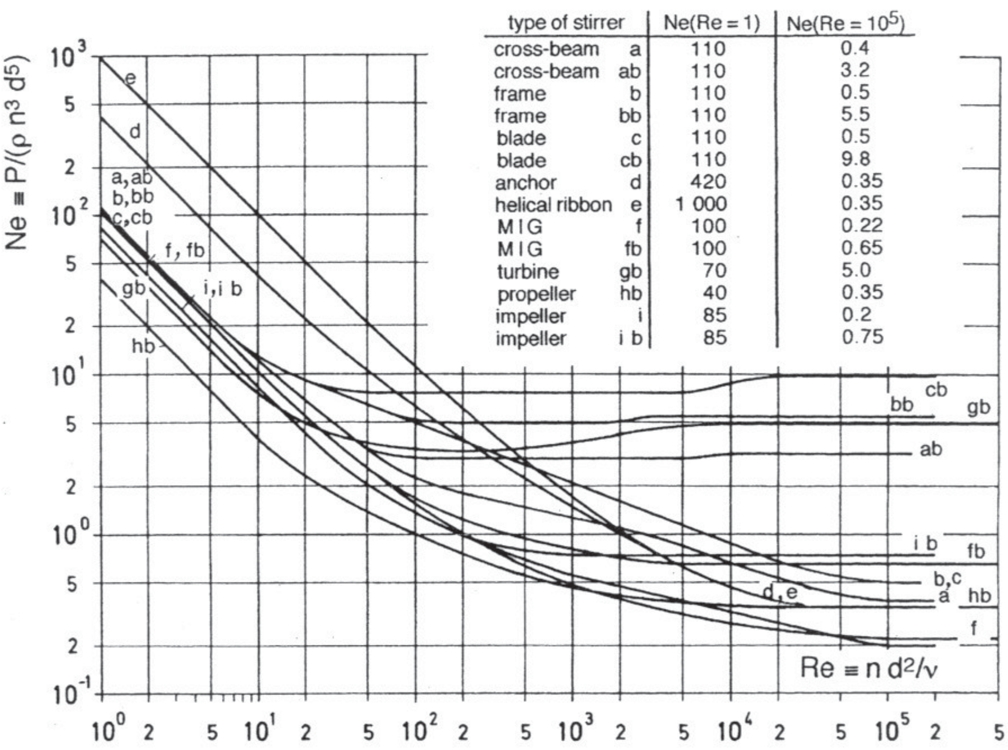


Figure 2.12: Power characteristic for a specific stirrer geometry (Zlokarnik 2001)

This result also confirms the pi-theorem, where five influencial quantities (stirrer diameter, fluid density, kinematic viscosity, stirrer speed and the mixing power as the target quantity) are reduced by the number of basic quantities (mass, length and time), and result in two dimensionless numbers. Gravity-caused impact, like the formation of vortices, is not considered in this approach. Implementing gravity, as another affecting quantity would result in a third dimensionless number, the Froude number.

From this dependent relationship, the stirring power can be easily determined by calculating the Reynolds number. The Newton number can be taken out of a diagram equal to Figure 2.12. The Ne-Re dependency is characteristic for different stirrer geometries (Figure 2.13).



type of stirrer		Ne(Re = 1)	Ne(Re = 10^5)
cross-beam	a	110	0.4
cross-beam	ab	110	3.2
frame	b	110	0.5
frame	bb	110	5.5
blade	c	110	0.5
blade	cb	110	9.8
anchor	d	420	0.35
helical ribbon	e	1 000	0.35
MIG	f	100	0.22
MIG	fb	100	0.65
turbine	gb	70	5.0
propeller	hb	40	0.35
impeller	i	85	0.2
impeller	i b	85	0.75

Figure 2.13: Power characteristics for different stirrer types

CHAPTER 3

EXPERIMENTAL METHODS

3.1 Pilot Plant

3.1.1 Plant overview

The pilot plant, employed in this study, has been designed with the objective of simulating the main treatment processes of a conventional drinking water treatment plant using surface water. The installed treatment processes are Pre-Oxidation, Coagulation, Flocculation, Sedimentation and Filtration with a dual media filter (Figure 3.1). Advanced water treatment processes like filtration with granulated activated carbon (GAC) are also established in this pilot plant. Expansion with other advanced water treatment processes like ozonation and UV-disinfection are planned. The pilot plant is controlled, and key data are collected by a SCADA (Supervisory Control and Data Acquisition) system. Two different user interfaces are available. One is designed to operate the plant from the local terminal located in the pilot plant laboratory. The second user interface is accessible through the World Wide Web with a web-browser. This tool makes key data like flow rate, temperature, turbidity, and pH accessible from a remote place and long-term tests can be monitored without being present on site.

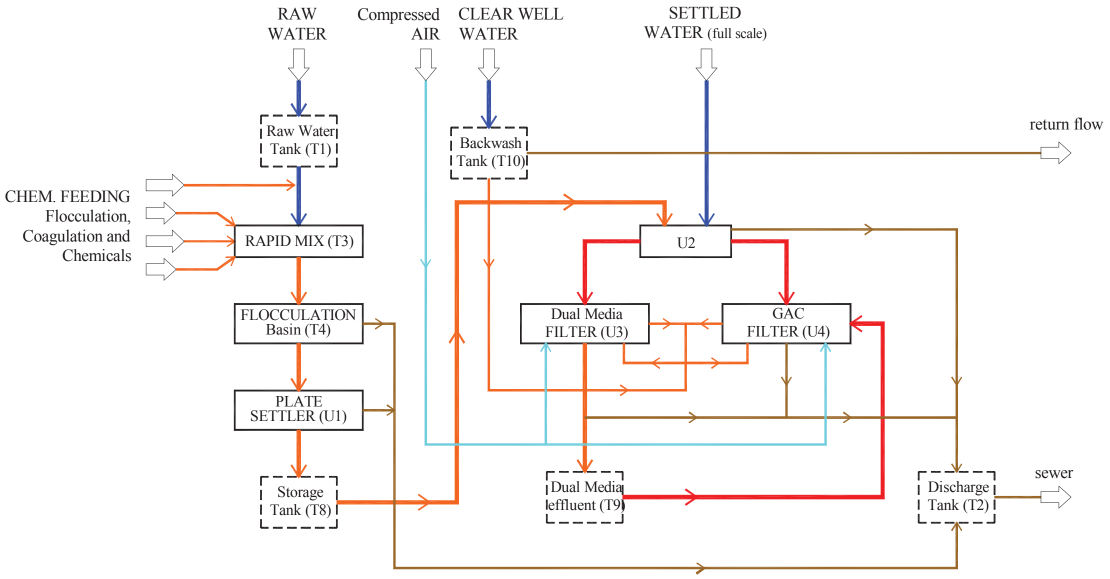


Figure 3.1: Schematic of the pilot plant

3.1.1.1 Process description[1]

Raw water is taken from the full-scale plant at the raw water building. It has to pass a screen (mesh width 5 mm) before it flows into a 250 gal (950 liter) raw water tank (T1). The pilot plant is primarily operated with constant flow, and the raw water tank acts as a plug-flow tank where a minor amount of solids settle out at the bottom of the tank. Traditional treatment processes like coagulation and flocculation are accomplished in the rapid mix reactor (T3) and the flocculation basin (T4). Besides adding coagulant and polymer, other chemicals for pH and alkalinity adjustment, as well as for softening purposes can be fed into the rapid mix reactor (P3, P4, P5). Prior to this chemical / physical treatment, an oxidant can be added (P10), immediately following the raw water tank (T1). After the flocculation basin the treated water passes a plate settler (U1), where sedimentation of the flocs occurs. The effluent of the settler can take two different paths. One is to drain the produced water into the discharge tank (T2), and the second is to pump (P8) the water into a storage tank (T8). T8 is situated on the floor above the filter columns. It has a capacity of 50 gallons (240 liters) and

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[1] Numbers in brackets refer to the overall process schematic in the appendix

provides a constant head for the filter columns. This water applies to the filter columns (U3, U4). Beside the water generated on pilot-scale, settled water from the full-scale plant can also be fed to the distribution column (U2) and passed through the filters (U3, U4). Each column is filled with a different filter media. One of them (U3) operates as a dual media filter with anthracite and sand as filter media, and the second column (U4) is filled with granular activated carbon (GAC). The filter columns can be operated individually, in series or in parallel mode. In serial mode the treated water from the dual media filter (U3) is transferred into a dual media effluent tank (T9) where a sink-pump (P7) brings the water to the top of the GAC filter column (U4). For backwashing purposes, water is taken from the clear well and stored in a backwash water tank (T10), where it is held until it is pumped (P6) through the filter bed. The backwash process can be assisted with air scouring.

The recorded data are fed into a Fieldpoint module (National Instruments), which sends the data to the terminal, located in the pilot plant laboratory. A graphical user interface, programmed in LabVIEW 6.1 (National Instruments) transforms the data from a current signal into flow, temperature, turbidity and pH readings. Through the LabVIEW program the chemical feeding pumps (P3, P4, P5, P10) sink-pumps (P7, P8) and several electrical valves (V3.1, V4.15, V4.32) are controlled. Historic data are stored in a database and are accessible through the LabVIEW program.

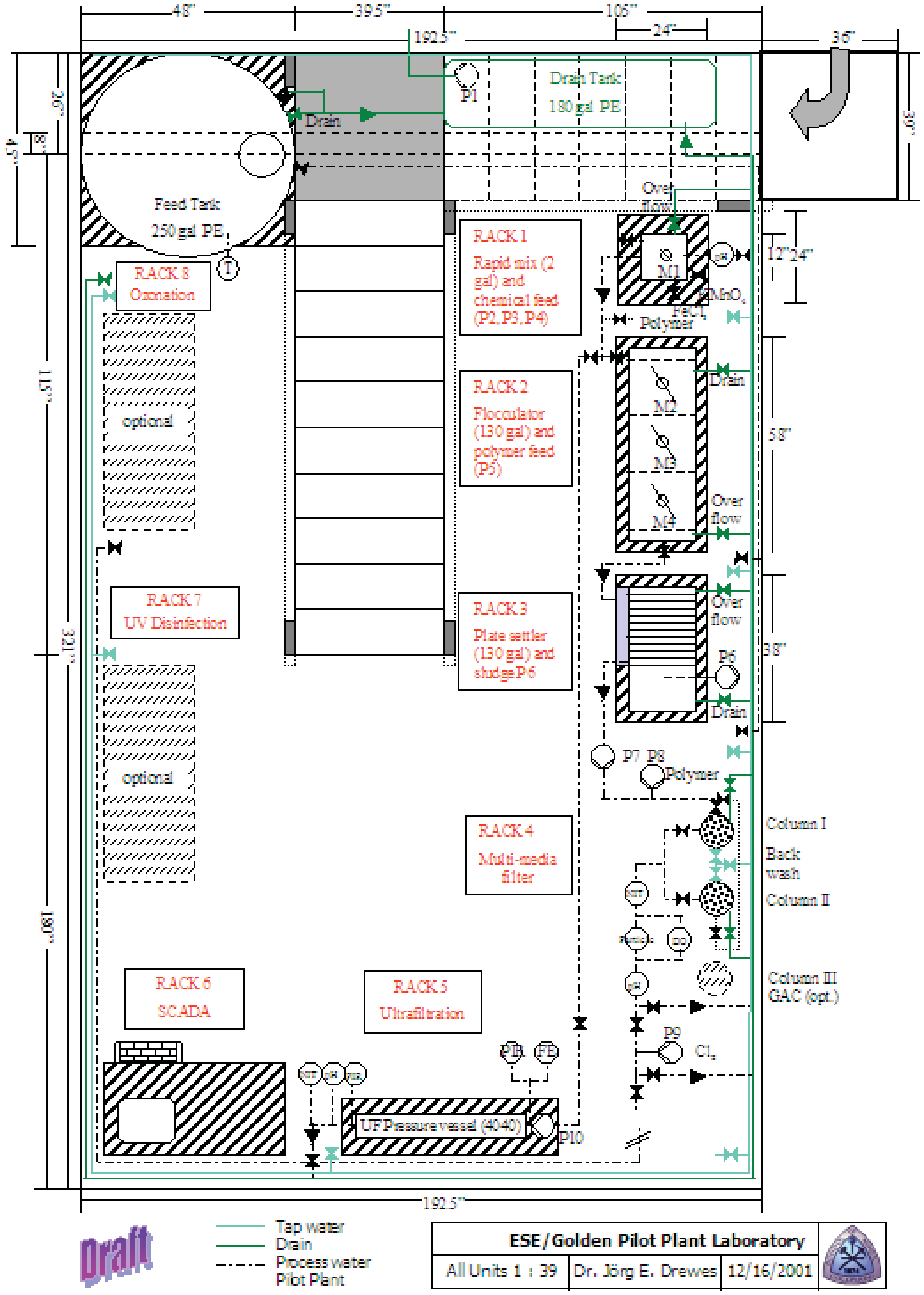


Figure 3.2: Ground plan pilot plant (not drawn to scale)

3.1.1.2 Design criteria

The pilot plant has a capacity of maximum of 3.7 gpm (0.233 L/sec) through rapid mix, the flocculation basin and the plate settler. Each filter column can treat a maximum flow rate of 1gpm (0.0631 L/sec). The design criteria are summarized in Table 3.1.

Table 3.1: Design criteria pilot plant - overall

Name	# from schematic	Specification / description
Main flow	T3, T4, U1	min. 0.5 GPM / max. 4 GPM
Flow through filter column	U2, U3, U4	max. 1 GPM
Raw water tank	T1	250 gal
Storage tank	T8, T9	50 gal
Backwash tank	T10	250 gal
Rapid mix reactor	T3	216x216x320 mm / wetted volume 9.7 liter / τ (retention time): 38 sec (4 gpm) to 154 sec (1 gpm)
Flocculation basin	T4	556x1752x650 mm / wetted volume 475 liter / τ (retention time): 31.4 min (4 gpm) to 125 min (1 gpm) / G(for chamber 1) 34s^{-1}, G(cha.2) 27s^{-1}, (cham.3) 14s^{-1}
Piping		PVC main flow 1”
Flow meter	FR01	GF Signet 2100 – Turbine Sensor/ GF Signet 8550 Flow Transmitter
pH sonde	QR01	GLI / Model 53
Turbidity DUAL	QR02	HACH 1720 C
Turbidity GAC	QR03	GLI Accu4 / Model 53

In order to determine the maximum theoretical flow rate, a hydraulic profile throughout the whole pilot plant was calculated (Figure 3.3, Table 3.2, Qasim et al. 2000).

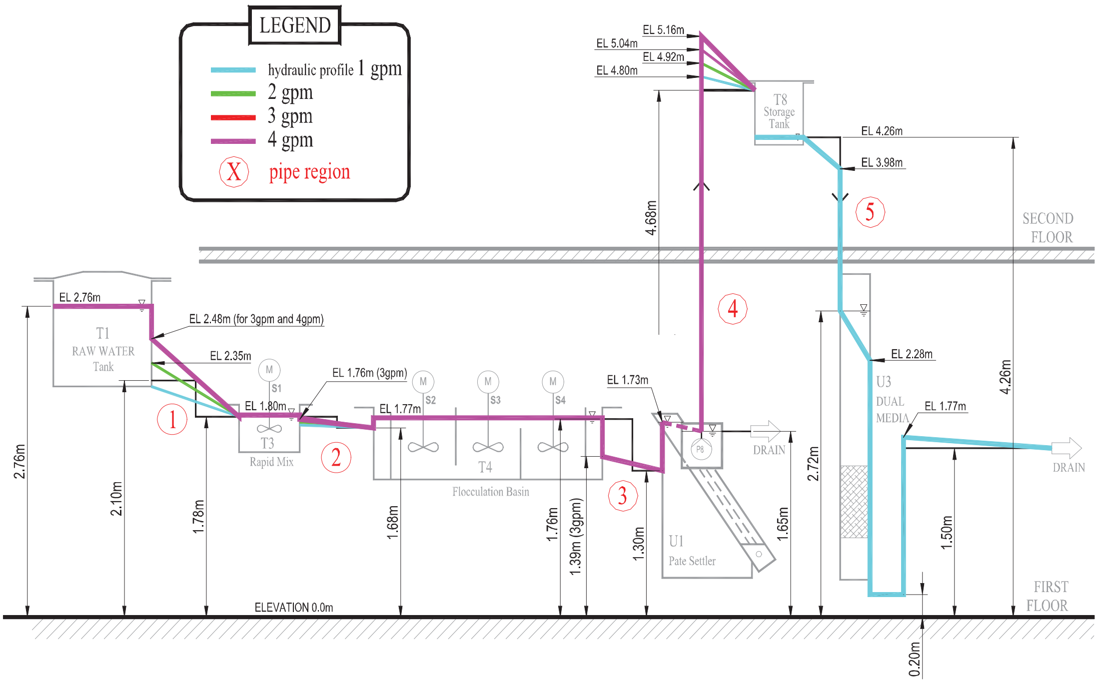


Figure 3.3: Hydraulic profile (not drawn to scale)

The hydraulic profile indicates three major head losses through pipe region 1, 4 and the filter bed (Figure 3.2, Table 3.2). The head losses through the pipe regions are represent the minor head loss due to inlet, outlet, fittings, valves and special fixtures (Qasim et al. 2000) and the friction head loss through pipes (equation of Darcy-Weisbach, Qasim et al. 2000). The head loss through the rapid mix and the flocculation basin are negligible and therefore not included in this calculation. To verify the head loss of the plate settler further investigation is necessary. The head loss through the filter bed was calculated with the empirical formula from Carmen-Kozeny (Qasim et al. 2000).

Table 3.2: Head loss calculations - summary

	1 gpm (0.0631 L/sec)	2 gpm (0.126 L/sec)	3 gpm (0.189 L/sec)	4 gpm (0.252 L/sec)
Pipe region 1 Raw water tank -> rapid mix	0.254 m	0.476 m	0.692 m	0.705 m

Tab. 3.2 cont.

Pipe region 2 Rapid mix -> flocculation basin	0.0253 m	0.0506 m	0.0758 m	0.101 m
Pipe region 3 Floc basin -> plate settler	0.0315 m	0.0629 m	0.0943 m	0.126 m
Pipe region 4 Plate settler -> storage tank	0.120 m	0.240 m	0.360 m	0.480 m
Pipe region 5 Storage tank -> filter column	0.280 m	-	-	-
Filter (normal flow)	0.441 m	-	-	-

3.1.1.3 Controls, adjustments and operation

The main flow rate can be adjusted through a ball valve (V1.5), which is located at the raw water tank effluent. This main flow rate is measured with a turbine flowmeter (FR01), before the water reaches the rapid mix.

Several safety features prevent an overflow of the processed water and enable continuous operation over a couple of days. The discharge tank (T2) contains two sink pumps (P1, P2) and a level indicator, which gives an acoustic signal at a defined level (LI±01). The dual media effluent tank (T9) is located below the level of the drainpipe for the pilot plant, which requires a pump (P9) to empty T9 and to force the filtered water on top of the GAC filter column. An overflow tank (T12) and a sink pump (P10) can handle potential overflows of the dual media effluent tank. Both filter columns (U3, U4) and the distribution column (U2) are directly connected to the drainage system through pipes.

3.1.2 Chemical feeding station

Chemicals can be added to the water stream before the water reaches the rapid-mix tank. This gives the added chemicals time to react with the water. Depending on the water flow rate the theoretical contact time varies from 45.7 sec (for 1 gpm) to 12.4 sec (for 3.7 gpm).

3.1.2.1 Process description

The chemical is added to the water stream with a diaphragm pump (P10). The pump works self-priming and sucks the applied chemical out of a 5 gal storage container (T11). Thorough mixing with the water is accomplished by hydraulic mixing. The tube from the pump pressure-side sticks about 60 mm into the main pipe and is installed perpendicular to the water stream.

3.1.2.2 Design criteria

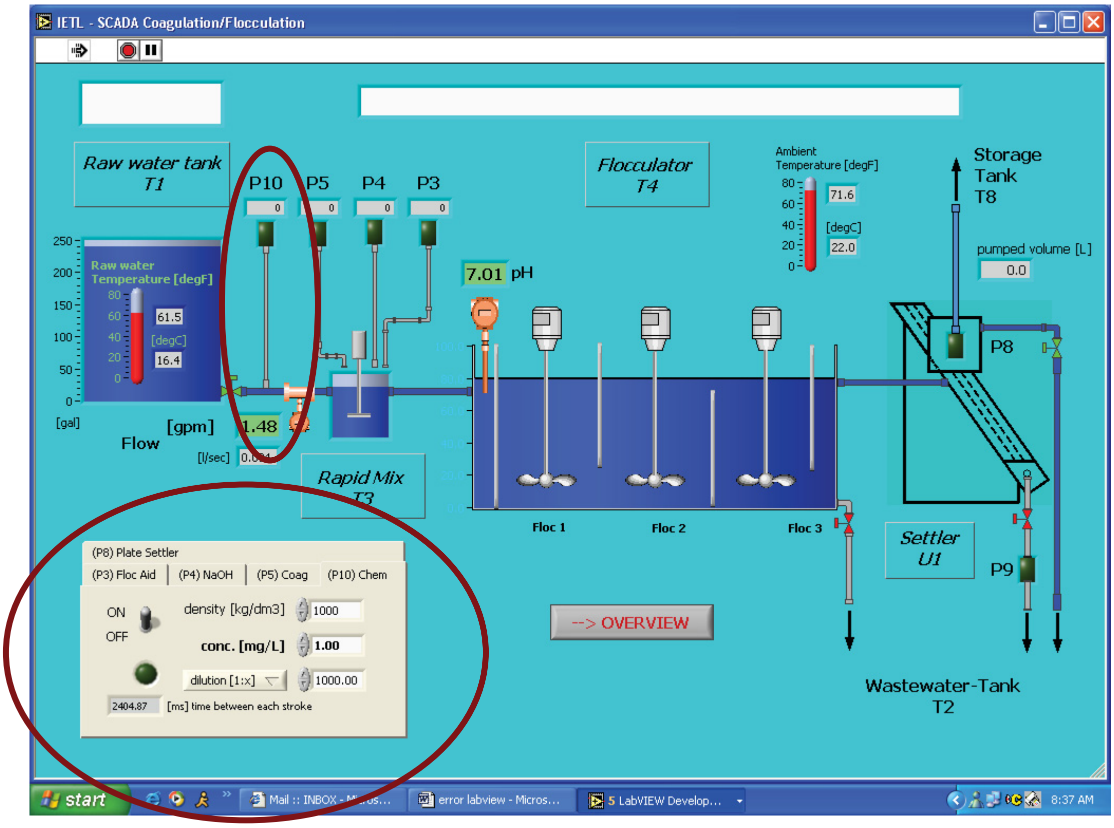
The design criteria are summarized in Table 3.3.

Table 3.3: Design criteria chemical feeding station (P10)

Name	# from schematic	Specification / description
Diaphragm pump	P10	Piston Diaphragm pump 16160 / max. 250 ul per stroke / max 2.6 psi / 3/16" piping
Tank for chemical	T11	5 gal
Piping		3/16" – 5/16" clear c-flex

3.1.2.3 Controls, adjustments and operation

The chemical feeding station can be controlled from the CoagSed front panel (see 3.1.7) of the Labview program (Figure 3.4).



raw water temperature: 61.5 [degF], 16.4 [degC]

ambient temperature: 71.6 [degF], 22.0 [degC]

pumped volume [L]: 0.0

flow [gpm]: 1.48

pH: 7.01

density [kg/dm3]: 1000

conc. [mg/L]: 1.00

dilution [1:x]: 1000.00

2404.87 [ms] time between each stroke

Figure 3.4: Chemical feeding station at the CoagSed Front panel

To adjust the set point concentration, several adjustments have to be made on the CoagSed front panel. The density and desired concentration of the added chemical, and the concentration of the stock solution are the necessary parameters to control the pump. The LabVIEW program uses these parameters and the measured flow rate to calculate a delay time (time between each stroke – Figure 3.4) and sends out a binary code to control the diaphragm pump. The mentioned stroke is a binary true-false signal, which turns the pump on and off. This on-off sequence is related to a specific pump volume (Figure 3.5).

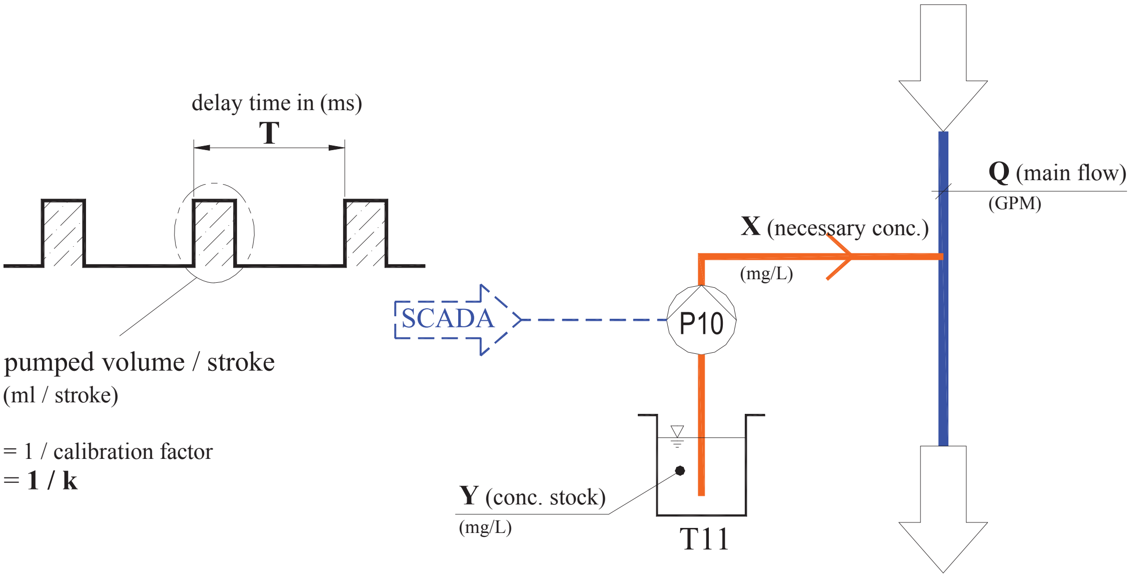


Figure 3.5: Control principle of the diaphragm pump

3.1.2.4 Calibration

The calibration of the diaphragm pump is achieved by counting the number of strokes required to suck 5 ml, 10 ml, and 15 ml out of a beaker. The calibration factor k (number of strokes / pumped volume) is calculated through linear regression (see also 3.1.3).

3.1.3 Rapid Mix chamber

Coagulation and **Flocculation** require the addition of chemicals to the water stream. Further water treatment such as softening, pH or alkalinity adjustment with lime or soda ash is also accomplished at the rapid mix chamber. The success of these processes depends on a rapid and thorough dispersion of the chemicals.

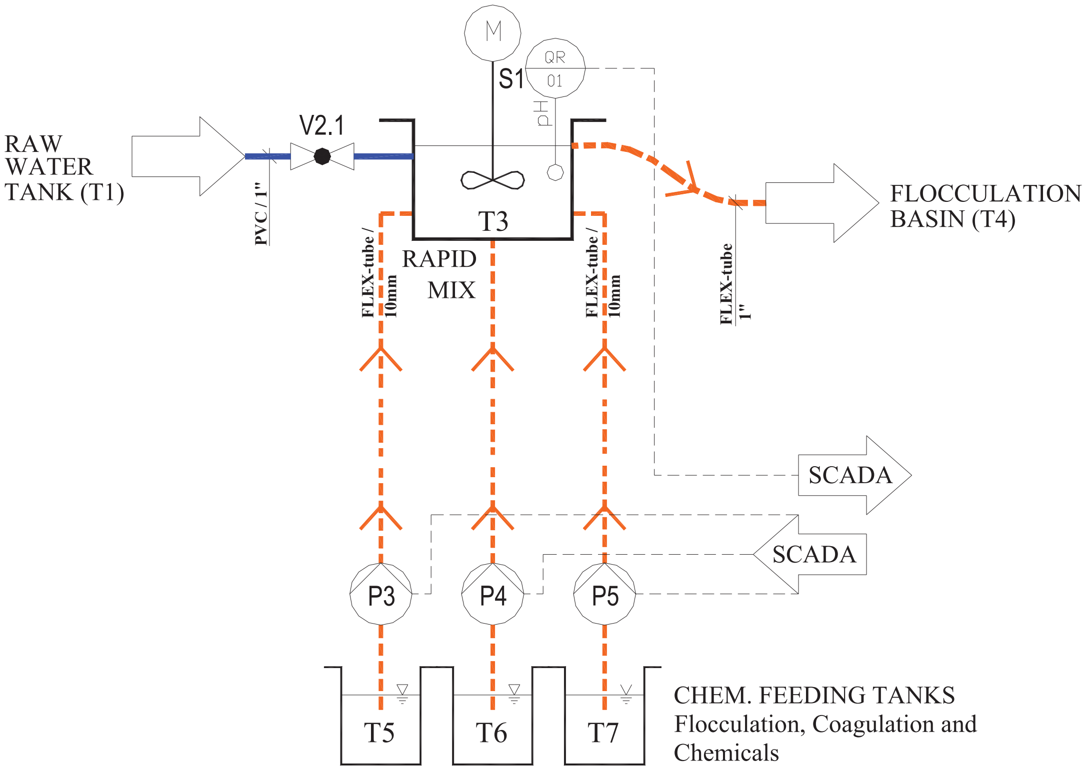


Figure 3.6: Schematic of the rapid mix chamber

3.1.3.1 Process description

The systematic structure of the unit operation is shown in Figure 3.6. The chemicals are added with diaphragm pumps (P3, P4, P5) out of the chemical feeding tanks (T5, T6, T7). Rapid mixing is carried out with mechanical mixing, with a three-plate propeller as an impeller (S1) to create turbulence in the mixing chamber (T3).

The chemicals added for coagulation are coagulant, polymer and a pH/alkalinity adjustment chemical. Raw water turbidity, temperature, alkalinity, pH, color, total organic carbon and chlorine demand affect the required dosage (Letterman et al. 1999). The chemicals in use and the applied dosages are usually based on jar testing of the raw water. In this pilot unit operation, equal to the full-scale, ferric ($Fe_2(SO_4)_3*9H_2O$) is used as the primary coagulant. The adjusted concentration is adopted from the full-scale plant. As a floc-aid, a nonionic polymer (Nalco 8181) is used both on full-scale and on pilot-scale. The applied polymer is too viscous to be added directly to the rapid mix chamber. To avoid clogging of the diaphragm pump (P3) and to guarantee a permanent chemical flow into the rapid mix reactor, the polymer has to be heated and diluted in a ratio between 1:100 and 1:300. Otherwise, thorough dispersion is impossible. The added coagulant needs to be diluted as well. A dilution ratio 1:10 was found to be a suffice value.

3.1.3.2 Design criteria

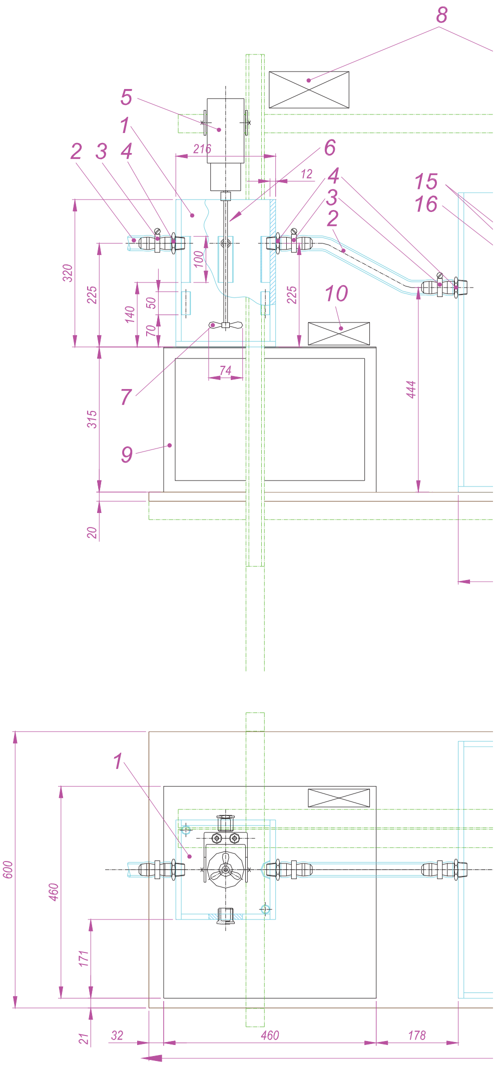
The design criteria are summarized in Table 3.4. Dimensions can be taken from Figure 3.7, which shows the setup of the rapid mix chamber.

Table 3.4: Design criteria for the rapid mix chamber

Name	**# from schematic**	**Specification / description**
Rapid mix reactor	T3	216x216x320 mm / wetted volume 9.7 liter / τ (retention time): 38 sec (4 gpm) to 154 sec (1 gpm)
Stirrer unit	S1	3” three blade propeller / Cole-Parmer Stir-Pak mixer head and speed controller, 60-6000 rpm /

Table 3.4 : cont.

Diaphragm pump	P3, P4, P5	Piston Diaphragm pump 16160 / max. 250 ul per stroke / max 2.6 psi / 3/16" piping
Tank for chemical	T5, T6	1000 ml / glass beaker
Tank for chemical	T7	2000 ml / plastic beaker



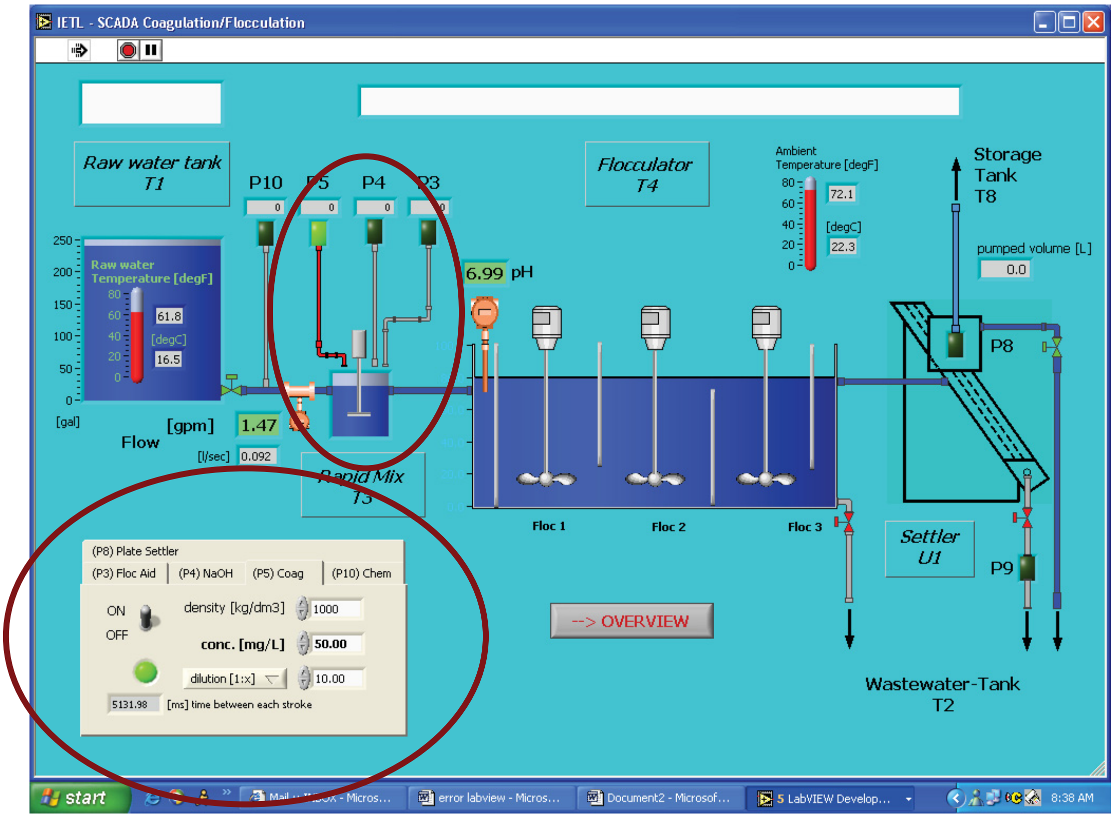
Legend:

1	Rapid mix reactor
2	Host 1"
3	Duct clamp 1"
4	Pipe nipple 1"
5	Stirrer motor
6	Stirrer shaft
7	Stirrer blade
8	Stirrer controller
9	Table

Figure 3.7: Drawing of the rapid mix chamber (dimensions in mm, not drawn to scale)

3.1.3.3 Controls, adjustments and operation

The operation of pump P3, P4, and P5 is controlled with a digital signal combination. These pumps are diaphragm pumps and are turned on and off with a true/false signal (stroke), provided by the SCADA system (Figure 3.4). Depending on the required concentration, the dilution factor, the density of the stock solution, and the magnitude of the main flow, the SCADA system calculates the delay time between each stroke. These parameters are adjusted on the CoagSed front panel on the terminal in the pilot plant (Figure 3.8). In order to achieve a thorough dispersion of the added chemicals throughout the whole water stream, the delay time should be in the range between 600 and 10,000 ms (time between each stroke – Figure 3.8). Therefore, the added chemicals need to be diluted. A 1:10 dilution for the coagulant and a 1:300 dilution for the polymer were found to be an appropriate value. To avoid clogging of the tubing the polymer dilution has to be heated and stirred on a stirring plate.



Ambient Temperature [degF] 72.1
[degC] 22.3
pumped volume [L] 0.0
6.99 pH
Raw water Temperature [degF] 61.8
[degC] 16.5
Flow [gpm] 1.47
[l/sec] 0.092
density [kg/dm3] 1000
conc. [mg/L] 50.00
dilution [1:x] 10.00
5131.98 [ms] time between each stroke

Figure 3.8: CoagSed front panel for rapid mix adjustments

3.1.3.4 Calibration

To calibrate the chemical feeding pumps, the number of necessary strokes, to fill up 5 ml, 10 ml, and 15 ml are counted and calibrated with a linear regression (Figure 3.9). This procedure differs to the chemical feeding station P10 (see 3.1.2).

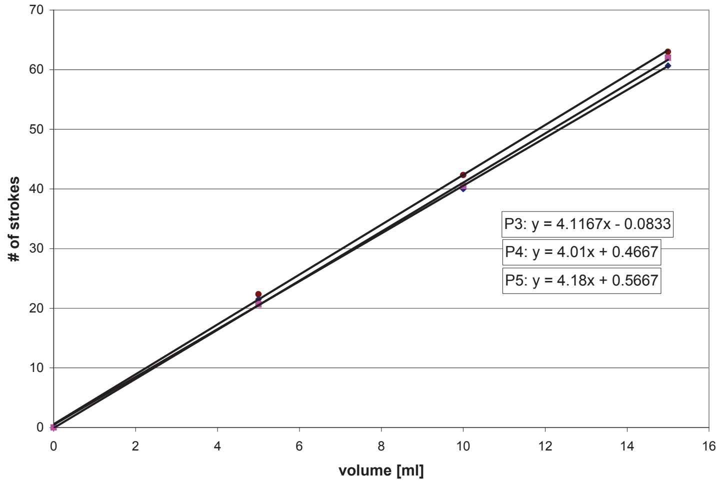


Figure 3.9: Calibration curve for P3, P4, and P5

The results of the linear regression need to be implemented in the LabVIEW program for the CoagSed front panel. The pump calibration is included in the calculation case structure (Figure 3.10).

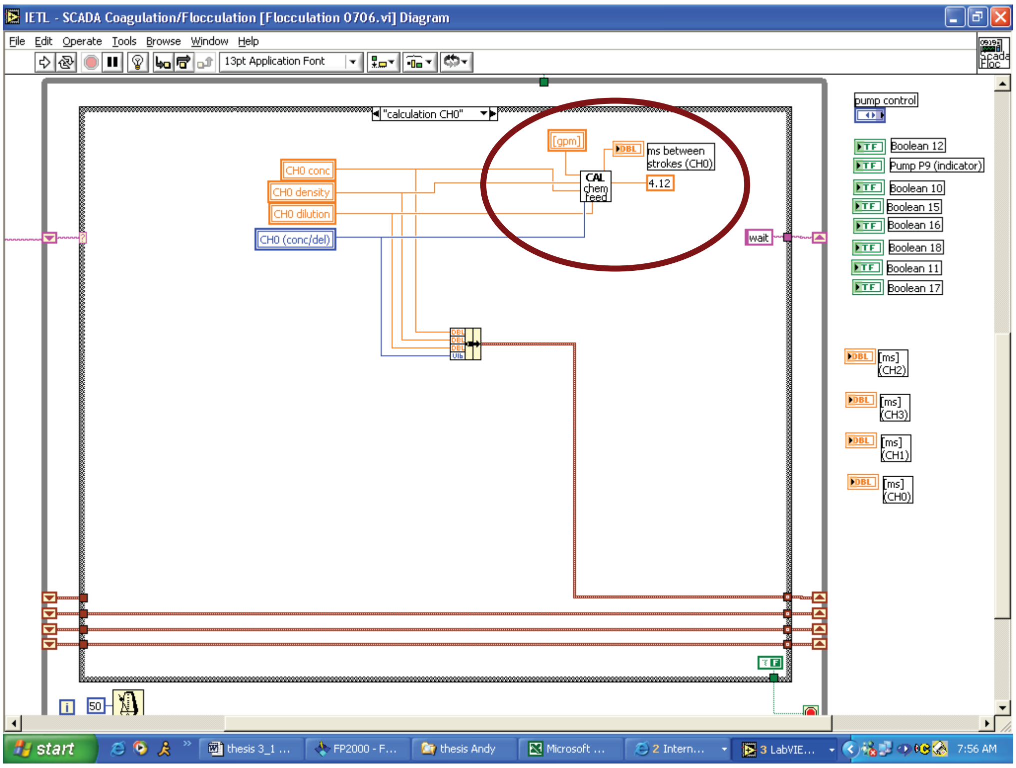


Figure 3.10: Flow diagram of the CoagSed front panel for pump calibration (see also 3.1.7)

3.1.4 Flocculation basin

Figure 3.11: Flocculation basin

The flocculation basin (T4, Figure 3.11) follows the rapid mix chamber (T3) where chemicals are added to destabilize the particles in the stream.

The purpose of flocculation is to form aggregates or flocs from finely dispersed particles and from chemically destabilized particles. Flocculation is a transport step that induces collisions between the destabilized particles, forming larger particles, which can be removed by settling or filtration (Tchobanoglous 2003). In this pilot plant, flocculation is accomplished in a separate basin (T4). This basin is designed with three separate chambers (Figure 3.12), where water flows down and up over the walls dividing the chambers.

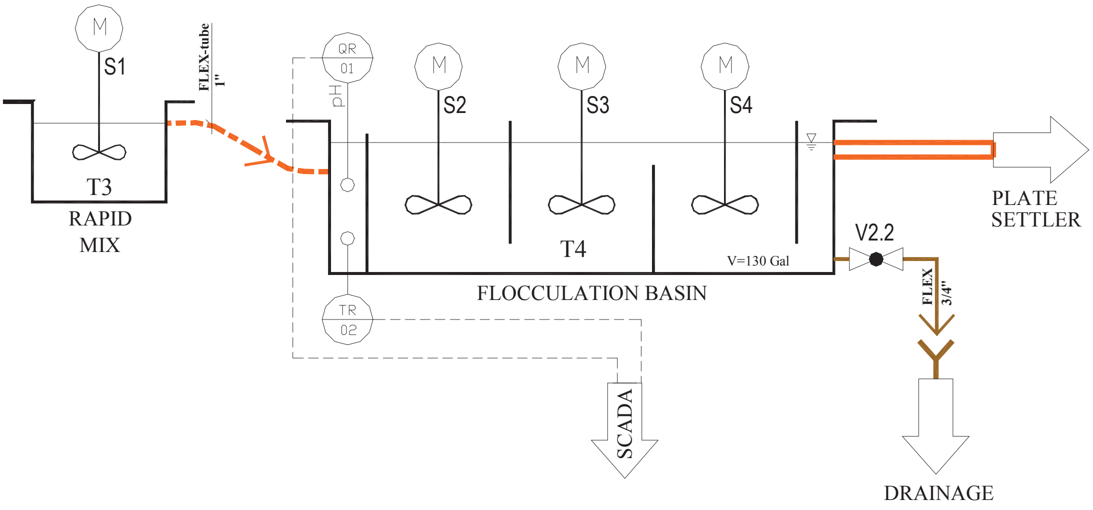


Figure 3.12: Schematic of the Flocculation basin

3.1.4.1 Process description

Flocculation mixing is achieved by using mechanical, variable speed mixers (S1, S2, S3). These mixers provide gentle mixing of the water to cause collision of the floc and form larger flocs, which settle and strain more easily.

An effective flocculation process involves the selection of the correct mixing time (retention time), the proper mixing intensity, the proper tank shape and appropriate equipment for uniform mixing. Insufficient mixing will result in ineffective collisions and poor floc formation. Excessive mixing may tear the flocculated particles apart by shear forces, after they have already clumped together. The pilot treatment units' theoretical hydraulic retention time for the whole flocculation tank is 62.7 min at a 2 gpm (0.13 L/sec) flow rate.

Temperature affects the flocculation process, because cold water is more viscous than warm water and thus more difficult to flocculate. A lower temperature requires faster mixing for increased turbulence (Qasim et al. 2000).

3.1.4.2 Design criteria

The design criteria are summarized in Table 3.5. Dimensions can be taken from Figure 3.13, which shows the setup of the flocculation basin. The velocity gradient (equation 2.13) for each flocculation chamber was calculated from the chamber volume, stirrer speed, viscosity, the Re number, and the Ne number (Figure 2.13, see also appendix).

Table 3.5: Design criteria for flocculation basin

Name	**# from schematic**	**Specification / description**
Flocculation basin	T4	556x1752x650 mm / wetted volume 475 liter / τ (retention time): 31.4 min (4 gpm) to 125 min (1 gpm) / G(for chamber 1) $34s^{-1}$, G(cha.2) $27s^{-1}$, (cham.3) $14s^{-1}$
Stirrer unit	S2, S3, S4	Cole-Parmer Stir-Pak mixer head and speed controller / 9-900 rpm
pH sensor	QR01	GLI / Model 53
Temperature probe	TR01	Cole-Parmer A-08439-6 / -310 to 1400 F

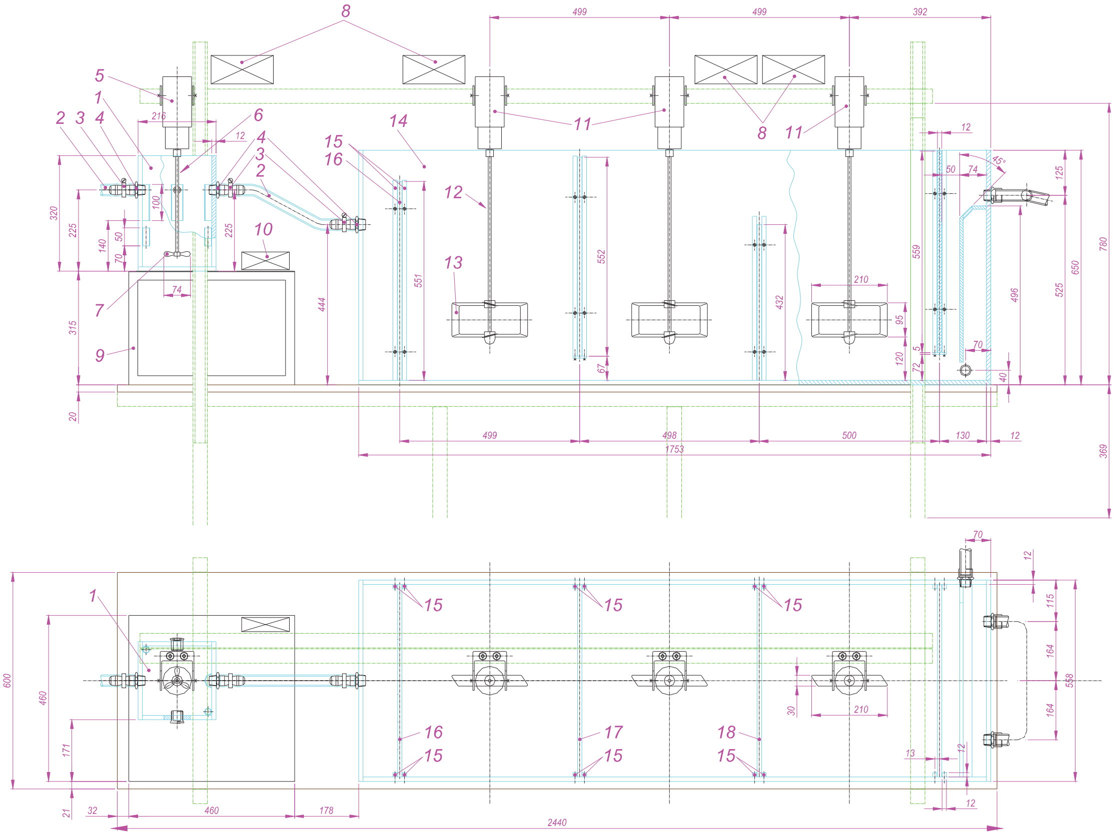


Figure 3.13: Drawing of the flocculation basin (dimensions in mm, not drawn to scale)

3.1.5 Plate settler

Figure 3.14: Plate settler

Sedimentation is a physical treatment process that utilizes gravity to separate suspended solids from water. This process is widely used as the first stage in surface water treatment to remove turbidity-causing particles after coagulation and flocculation. Sedimentation is also used to recover water in filter backwash water recovery systems, and increases the sludge solid concentration during sludge thickening. Pre-sedimentation is also used in some cases to remove heavier solids such as gravel, grit and sand from river water before it is pumped to the treatment plant.

The plate settler (Figure 3.14), which is used as the sedimentation facility in the pilot plant, is a shallow settling device that consists of stacked offset trays. The efficiency of the settling process in a plate settler depends on the settling area rather than detention time. This type of facility is used predominately in water-treatment applications and also in wastewater-treatment.

Plate settlers are usually set at an angle between 45° and 60° above the horizontal. When the angle is increased above 60°, the efficiency decreases. If the plates are inclined at angles less than 45°, solids will tend to accumulate on the plates.

To control biological growth and the production of odors (the principal problems encountered with their use), the accumulated solids must be flushed out periodically (usually with a high pressure water). The need for flushing poses a problem with the use of plate settlers when the characteristics of the solids to be removed vary daily.

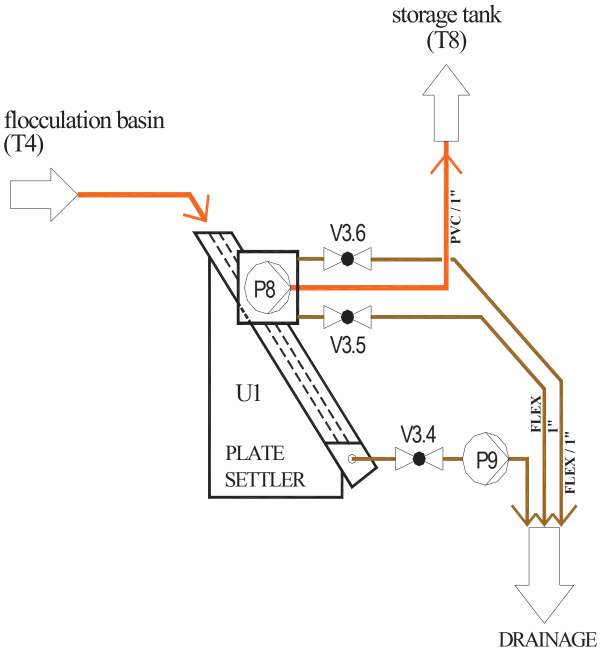


Figure 3.15: Schematic of the plate settler

3.1.5.1 Process description

Figure 3.15 shows the principle structure of the plate settler installed in the pilot plant. The effluent of the flocculation basin flows directly into the plate settler. At the inlet the water is forced to flow down and passes three plates on the way to the outlet. After passing the plates, the clear water is collected in an effluent box on the side of the plate settler. The sink pump P8, which is located in this effluent box, pumps the settled water up to the storage tank T8. This effluent box has two drains that are connected to the drainage system. Usually, the upper one is open that the box is able to fill to the upper drain. This allows a continuous operation and P8 can be operated through the SCADA system (Figure 3.16) from the CoagSed front panel.

3.1.5.2 Design criteria

The design criteria are summarized in Table 3.6. Dimensions can be taken from Figure 3.16, which shows a detailed drawing of the plate settler.

Table 3.6: Design criteria for plate settler

Name	**# from schematic**	**Specification / description**
Plate settler	U1	Design flow: 0.5 to 4 GPM Wetted volume: 152 liter 6/4” pipe connection (inlet)
Sink pump	P8	Little Giant / Model 5MSP
Sludge pump	P9	Dayton DC Gearmotor / 4Z129A Cole-Parmer Masterflex tube-holder / Model 7019-32

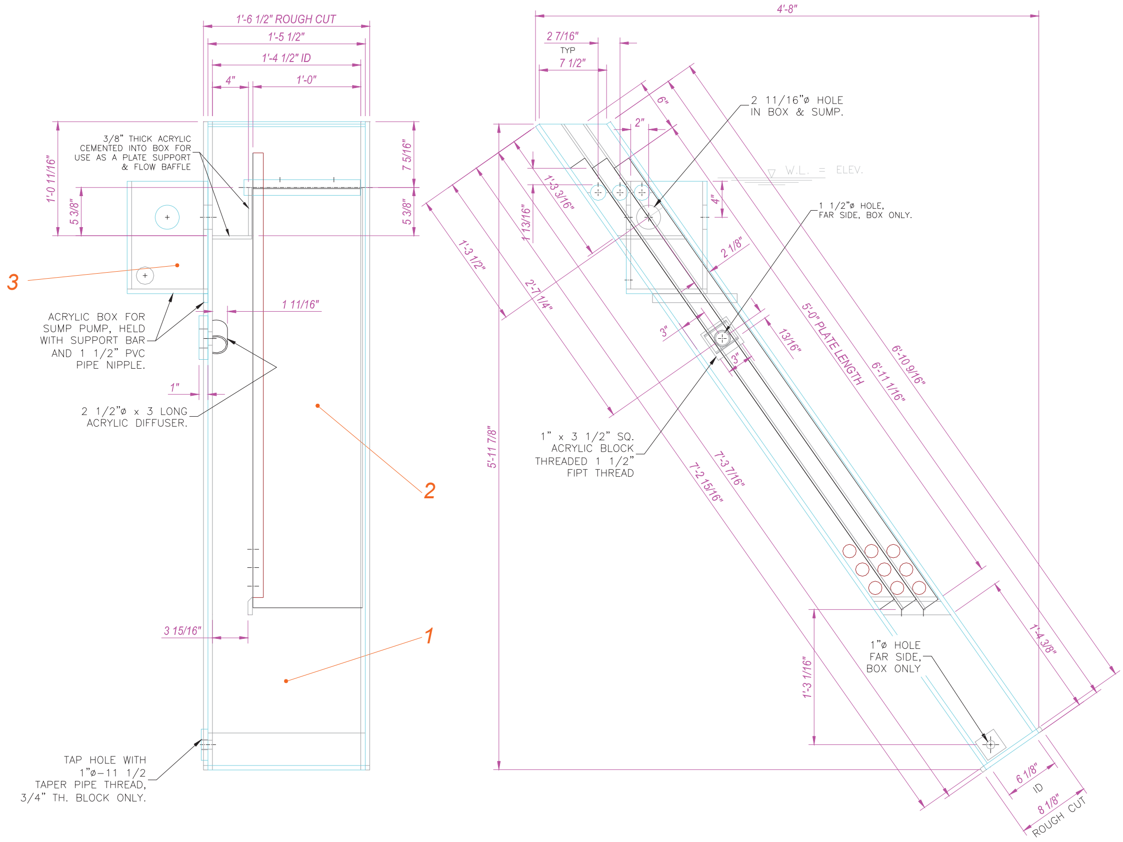
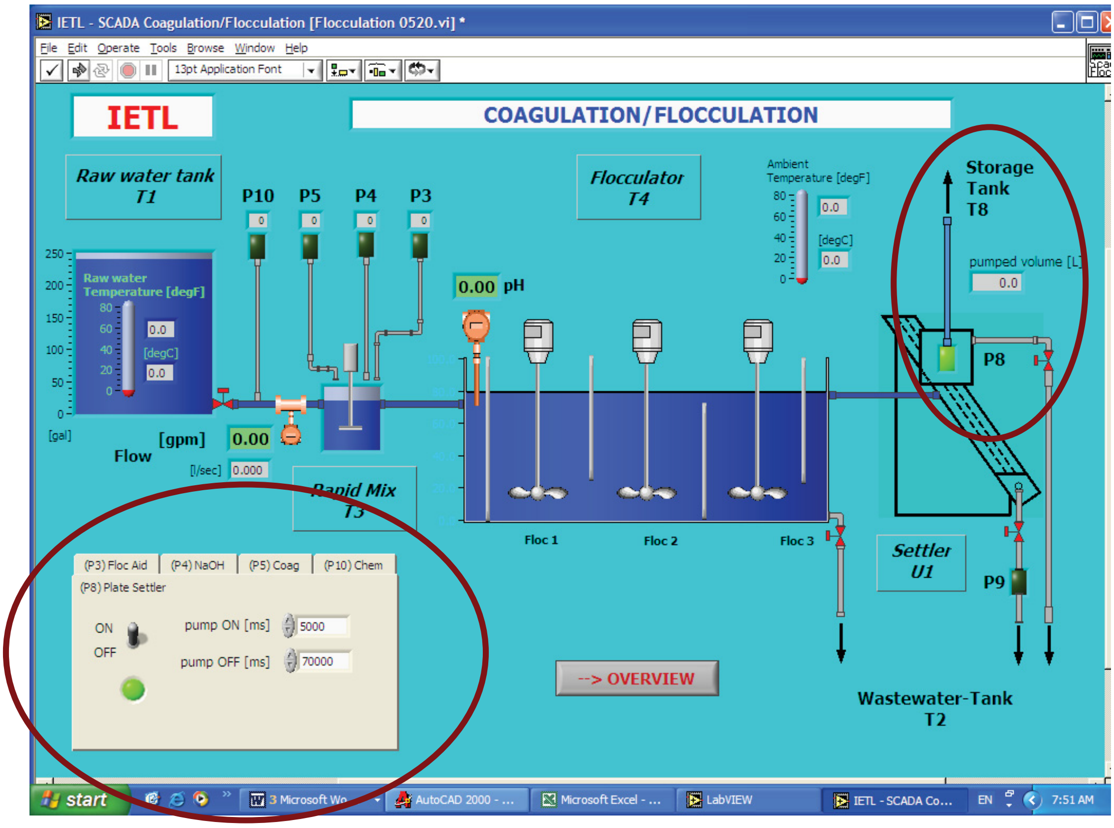


Figure 3.16: Drawing plate settler (dimensions in inch, not drawn to scale) (Meurer Research Inc.)

3.1.5.3 Controls, adjustments and operation

To control the settler effluent pump (P8), a pumping time (pump ON) and a delay time (pump OFF) must be determined on the front panel (Figure 3.17). To simulate a constant head tank with this setup, a pumping time of 5,000 ms and a delay time of 70,000 ms, for a maximum flow rate of 1 gpm through the filter columns, turned out to be appropriate values. This assumes that the filter columns are operated in individual or serial mode.



pump ON [ms] 5000

pump OFF [ms] 70000

Figure 3.17: CoagSed front panel for P8

In order to clean the settled flocs from the settler, the valve V3.4 has to be opened and the sludge is pumped (P9) through the drainage system into the discharge tank (T2). To clean the settler entirely, the main water supply has to be turned off and the whole settler should be drained through P9. Periodically the individual plates should be cleaned; and therefore the plates need to be pulled out of the settler. The cleaning intervals for the plates are usually less frequent (once a month during permanent operation) than the sludge removal process (once a week).

3.1.6 Filter column

Figure 3.18: Filter columns

Filtration is installed as the final treatment step in this pilot plant. The filtration process is operated in filter columns (Figure 3.18) with a diameter of 6 inch (15 cm). Successful simulation of filtration in filter columns with a diameter larger than 4 inch (10 cm, Stoops 2000) has been reported. Smaller columns have an excessive sidewall-to-surface ratio, which results in significant short-circuiting along the column walls during the filter operation. Both filter columns are gravity operated.

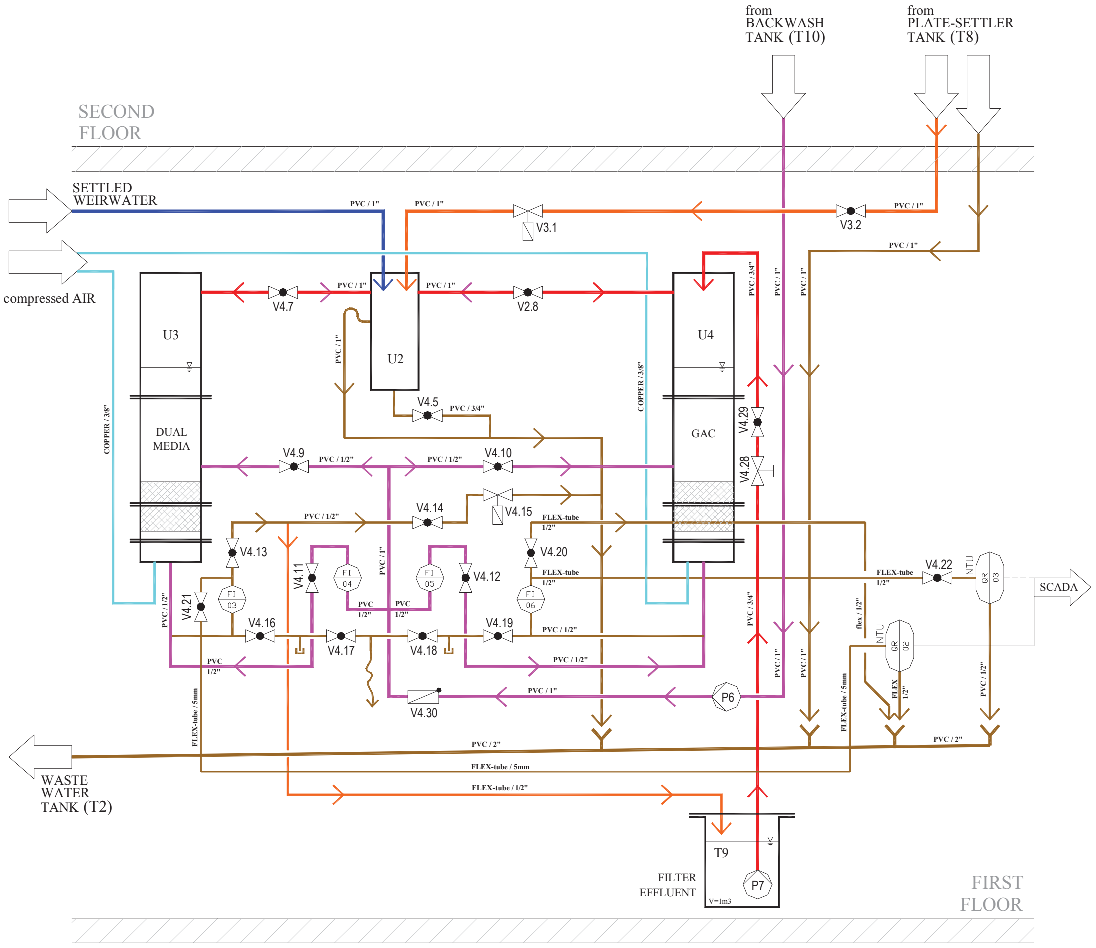


Figure 3.19: Schematic of the filter columns

3.1.6.1 Process description

The filtration unit of the pilot plant is designed as a two-stage filter unit. Both filter columns (U3, U4) can be run in parallel or in serial mode. In both modes, the influent water runs through the distribution column (U2) from the point where the water is delivered to the main filter columns. If the filter columns are operated in serial mode, the settled water (full-scale or pilot-scale) runs through the dual media column (U3). To guarantee a constant flow and to get an actual turbidity reading (QR02), the ball valves V4.13, V4.14 and V4.21 have to be opened. The filter effluent can be drained into the wastewater tank (T2) through the drainage system or it can fill the filter effluent barrel (T9). Therefore the valve V4.15 has to be opened through the SCADA-system (Figure 3.20) by activatiog the valve-symbol. Turning on the GAC-pump (P7), and opening the valve V4.32 drains the filter effluent barrel. This can be achieved from the Filtration front panel (Figure 3.20).

In order to run the second filter column (U4) which is filled with granular activated carbon (GAC). The GAC-pump P7 has to be turned on through the SCADA-system (Figure 3.20). Additionally, the ball valves V4.20 and V4.22 have to be opened and V4.15 needs to be closed. As with the dual media filter column, the filter effluent is diverted in a sample stream for turbidity reading (QR03) and a drainage stream that drains into the wastewater tank (T2).

To avoid water overflow several safety features are installed. Each column (U2, U3, U4) has a physical overflow. If the water rises above a certain level, fixed pipes transport the water to the drainage system. If the filter effluent barrel (T9) overflows, a 5 gal barrel (T12) collects the water and a constantly operating sink pump (P11) pumps the water into the drainage system.

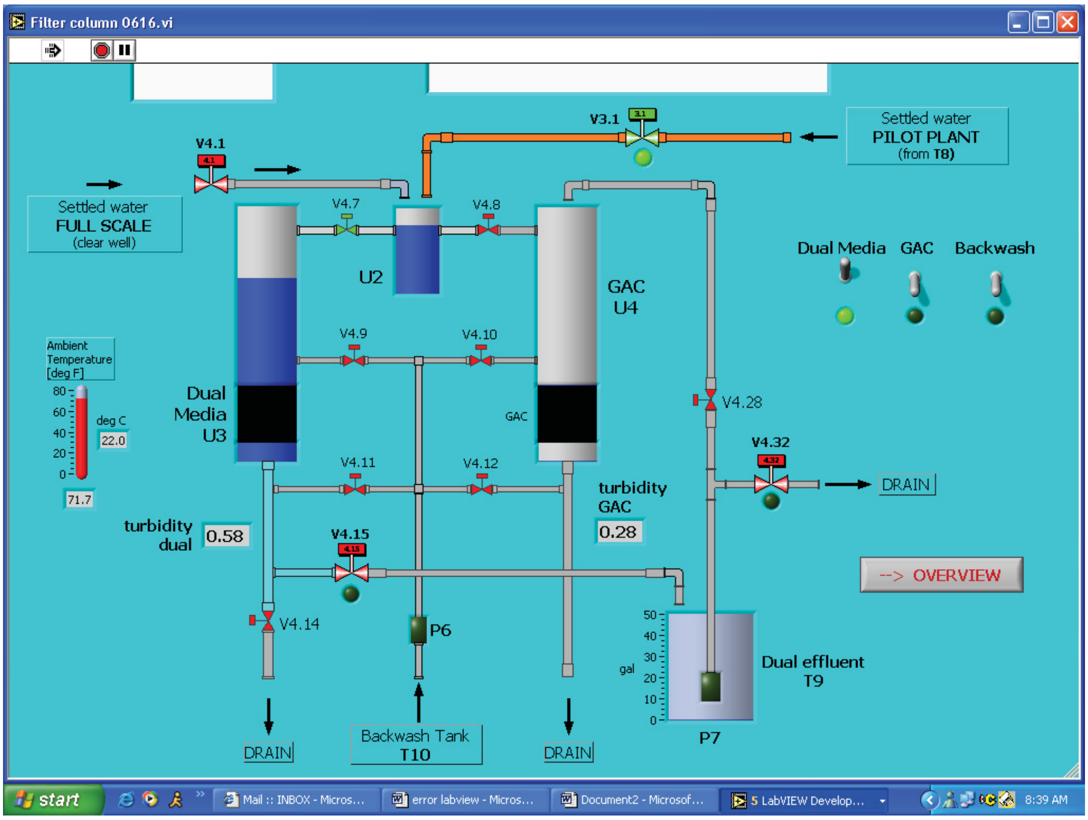


Figure 3.20: Filtration front panel

To guarantee smooth operation of both filter columns, a backwash procedure is necessary. Depending on the raw water turbidity the dual media should be run in backwash intervals of one to two days. The backwash water is stored in a separate tank (T10) and it is taken from the full scale clear well. The back wash pump (P6) is operated manually with a switch, which is located at the SCADA terminal. Additional to the water flow from the bottom, the backwash process can be supported by compressed air. Depending on which column is being backwashed, the valves V4.3 or V4.5 need to be opened.

3.1.6.2 Design criteria

Each filter column is filled with different filter media. U3 is filled with anthracite and fine sand. The second filter column (U4) is filled with GAC. For further detail see Table 3.7. Dimensions can be taken from Figure 3.21, which shows the setup of a filter column.

Table 3.7: Design criteria filter column

Name	**# from schematic**	**Specification / description**
Distribution column	U2	∅6” / material: acrylic 1” pipe connection (inlet)
Filter column Dual Media	U3	∅6” / anthracite and fine sand / 64 cm height total /
Filter column GAC	U4	∅6” / Filtrasorb F300 (Calgon Carbon Corp.) / 75 cm height /
GAC pump	P7	Little Giant 2E-N
Backwash pump	P6	Dayton
Overflow pump	P11	Little Giant 5 MSP
Electrical valve	V3.1, V4.15, V4.32	Buerkert / 2/2 way solenoid valve / 120V 6213A 1/2” NBR-BR /
Turbidity dual media	QR02	HACH 1720 C

Table 3.7 cont.

Turbidity GAC	QR03	GLI Accu 4 / Model 53
Flow indicator – Filter eff.	FI03, FI06	KING 0.1 – 1 gpm
Flow indicator – backwash	FI04, FI05	KING 0.5 – 5 gpm
Flow indicator - compressed air	FI01, FI02	KING 5 – 40 SCFM – air - STD
Storage tank	T8	50 gal
Filter effluent barrel	T9	50 gal
Backwash tank	T10	350 gal
Overflow tank	T12	5 gal

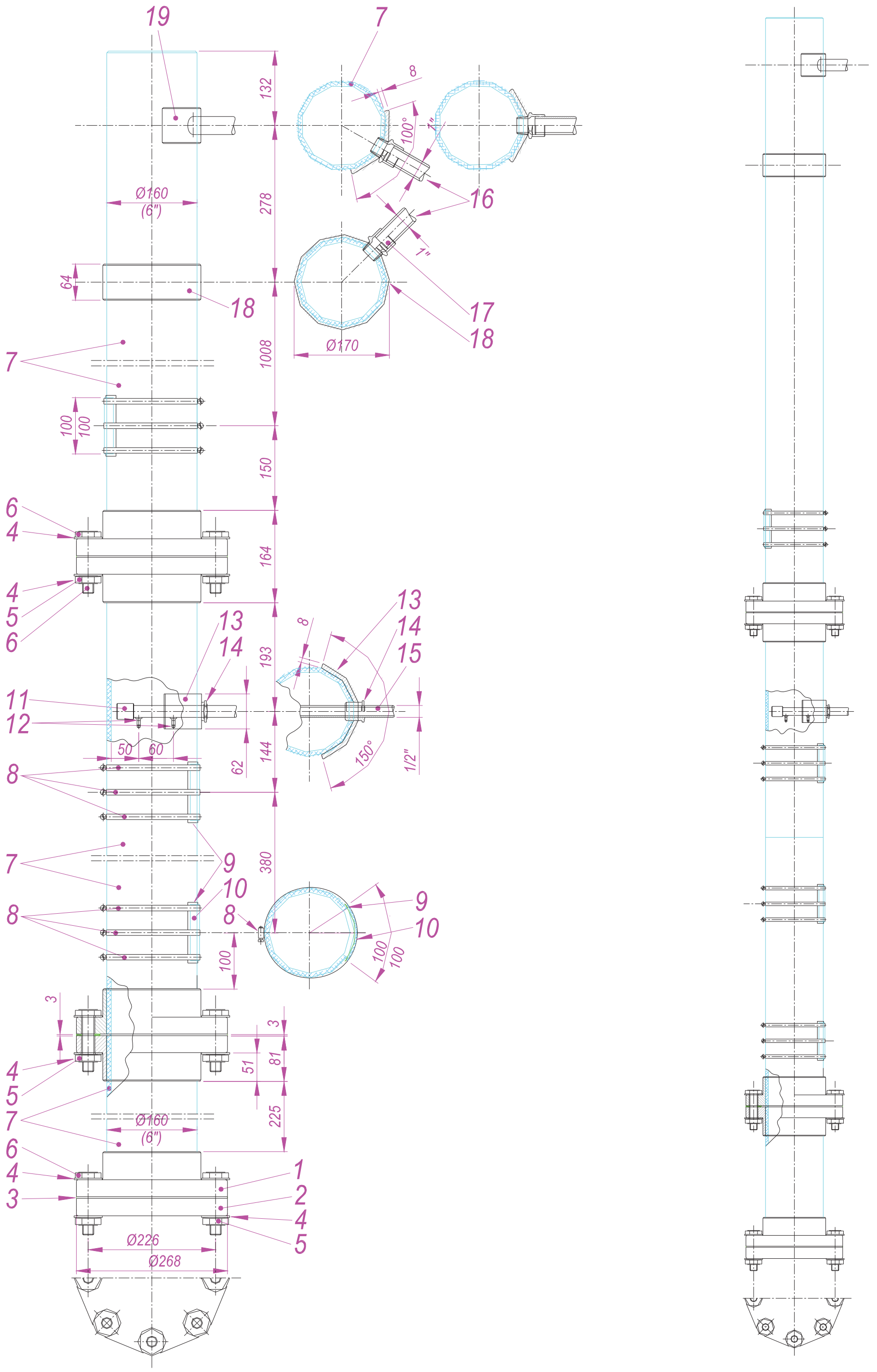


Figure 3.21: Schematic of the filter column (dimensions in mm, not drawn to scale)

3.2 Analytical Methods

Samples collected during this study for water quality analysis represent grap-samples. Experience on full-scale showed consistent, reliable raw water quality at least throughout the period of a conducted study using the pilot plant.

3.2.1 Flow

Flow is measured with a turbine flowmeter (GF Signet 2100 Sensor / GF Signet 8550 Flow Transmitter). The flowmeter was calibrated for the SCADA system accomplished through linear regression with a defined water volume and the necessary filling time.

3.2.2 pH

The pH after the rapid mix is measured online with a GLI Differential pH sensor. The output signal is fed into a pH analyzer (GLI model P53) and from there to the SCADA system. The pH sensor is temperature compensated with an implemented thermistor. The determined temperature can be read at the display of the pH analyzer. The pH meter was calibrated with pH 4, pH 7, and pH 10 calibration standards.

3.2.3 Temperature

Measurements for water and ambient temperature are taken with a standard industry temperature probe (Cole-Parmer A-08439-6 / -310 to 1400 F). The temperature is measured and stored through the SCADA system. Equal to the other online instruments, calibration is based on linear regression.

3.2.4 Conductivity

Tracer tests were carried out with a hand held conductivity meter (YSI 30). The temperature was reported throughout the tracer test.

3.2.5 Turbidity

Turbidity from the effluent stream of the two filter columns is measured permanently with online turbidity meters (HACH 1720C, GLI T53-8320). The taken measurements are sent to the SCADA system and saved in a database. Several samples were taken from the process stream after certain treatment steps and measured with a laboratory turbidity meter (HACH Model 2100N). All instruments are electronic nephelometers, where the scattered-light detectors are located at 90 degree to the incident beam.

3.2.6 Manganese

The concentration of dissolved manganese (Mn^{2+}) was measured with a colormetric method performed on a HACH DR4000 Spectrophotometer at a wavelength of 560 nm (method 8149 for Mn concentration up to 0.7 mg/L). A detection limit of 0.003 mg/L was determined (DeJong et al. 2003). In order to analyze the concentration of dissolved manganese the samples were filtered with a 0.2 µm cellulose acetate filter (MFS 47mm) and afterwards forced through a 0.02 µm, disposable syringe filter (Whatman Anotop 10). Further on, ascorbic acid is added to reduce all oxidized forms of manganese to Mn^{2+}. To mask any potential interferences an alkaline-cyanide reagent is added followed by the addition of the PAN Indicator (0.1 %), which combines with Mn^{2+} to form an orange complex. The detection wavelength is 560 nm.

3.2.7 Ultraviolet Absorbance (UVA)

Ultraviolet Absorbance was measured with a single beam spectrophotometer (Perkin Elmer, model Lambda 11). The samples were filtered with a 0.45 µm cellulose acetate filter (MFS 53BAFC 47mm) and analyzed with the standard wavelength of 254 nm. Because of the expected low UV ranges the UV-absorbance was measured with a 5 cm cell. Zero absorbance, using DI-water was checked and if necessary corrected after each sample. The specific UV absorbance

(SUVA) was determined by calculating the ratio between UV absorbance and the DOC data.

3.2.8 Dissolved Organic Carbon (DOC)

The dissolved organic carbon of the filtered water samples (0.45 µm cellulose acetate filter / MFS 53BAFC 47mm) was carried out with a Sievers 800 Portable Total Organic Carbon Analyzer in combination with a Sievers autosampler system (model 800AS). The detection limit of this instrument is 0.05 ppb. The Sievers 800 measures DOC with the wet oxidation method. Within this method the samples are acidified with phosphoric acid (H_3PO_4) that converts the inorganic carbon (IC) into carbon dioxide, which is detected by the IC-CO_2 sensor. In a second stream organic carbon is oxidized with ammonium persulfate ($(NH_4)_2S_2O_8$) in the presence of ultraviolet light. The resulted carbon dioxide is measured by a sensitive membrane-based conductometric technique. The concentration of inorganic carbon is subtracted from the total DOC concentration for each measurement. In this way the amount of organic compounds are determined.

CHAPTER 4

RESULTS and DISCUSSION

4.1 Hydraulic Tracer Test

The hydraulic pattern of the installed unit operations was determined with tracer tests. In order to determine a breakthrough curve for each unit operation and section (Figure 4.1) of the pilot-plant, the influent water was spiked with a sodium chloride solution (1,600 to 2,000 mg/L). The concentration in the effluent was measured with a conductivity meter.

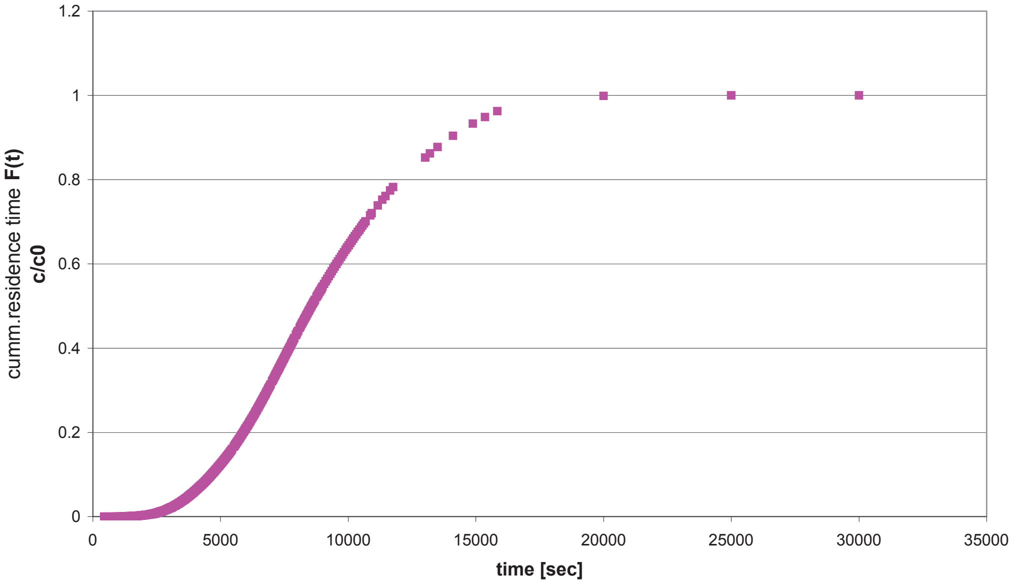


Figure 4.1: Breakthrough curve from the raw water tank to plate settler effluent

Table 4.1 shows a summary of identification numbers, determined from the breakthrough curves.

Table 4.1: Characteristic values for unit operations

	flow	volume	τ[1]	t_{10}[2]	t_{50}[2]	t_{90}[2]	MDI[3]	1 / MDI[4]	t_{50}/τ[5]
	[L/sec]	[L]	[sec]	[sec]	[sec]	[sec]	[-]	[%]	[-]
Rapid Mix Reactor	0.13 (2.2gpm)	9.7	75	19.1	58.1	110	5.8	17.4	0.77
Flocculation Basin	0.13 (2.2gpm)	475	3650	757	1760	3300	4.4	22.9	0.48
Plate Settler	0.13 (2.2gpm)	152	1180						
Raw water tank to Settler effluent	0.11 (1.7gpm)			4550	8540	13900	3.1	32.8	
Filter Column	0.13 (1gpm)			449	921	1360	3.0	33.0	

The ratio t_{50}/τ represents the index of the mean retention time, which is an indicator of the skew of the residence time distribution (RTD) curve. In an effective plug-flow reactor, the RTD curve is similar to a normal Gaussian distribution (U.S. EPA 1986). The rapid mix chamber and flocculation basin show t_{50}/τ ratios smaller than 1.0. These indicate RTD curves, which are skewed to the left.

The Morrill dispersion index (MDI) is based on sedimentation studies (Morrill 1932) and is defined as the ratio between t_{10} and t_{90}. The MDI for an ideal plug-flow reactor is 1.0 and about 22 for a complex-mix reactor (Tchobanoglous et al. 2003). A plug-flow reactor with an MDI value of 2.0 or less is considered by the U.S.EPA as an effective plug-flow reactor (U.S.EPA 1986). The reciprocal

---

[1] Theoretical hydraulic residence time (volume / flowrate)

[2] Time a witch 10, 50, and 90 percent of the tracer had passed through the reactor

[3] Morrill dispersion index (t_{10} / t_{90})

[4] Volumetric efficiency as defined by Morrill (1932)

[5] Index of mean retention time

value indicates the volumetric efficiency of a reactor. The MDI values which are greater than 3 and the volumetric efficiencies below 35 % in all unit operations (Table 4.1) indicate a low mixing performance. Improvements with different stirrer types and baffles could warrant further research.

4.2 Baseline Performance Test

3.1.1 Coagulant ($Fe_2(SO_4)_3*9H_2O$) Concentration

In the pilot-plant the same coagulant concentration as in full-scale was added to the raw water. To determine the most effective coagulant dosage without pH adjustment, the FlocAnalyzer (ClearCorp) was used. The FlocAnalyzer uses an optical probe to monitor the flocculation process in a 2-liter reactor vessel. The particle cross-section and the number of particles, which flow through the probe, are determined with a 0.3 mm blue light beam and a photo detector. The detected signal is analyzed with the FlocAnalyzer (Figure 4.2). The FlocAnalyzer determines the Floc-Particle Size (equation 4.3), which is defined as a function of the Floc-Particle Cross-section (equation 4.1), and the amount of produced flocs (equation 4.2).

$V_{rms} = \int(\text{Raw Signal})\, dt$ Floc-Particle Cross-section (4.1)

$N_p = \sum(\text{number of signal peaks})$ Floc-Particle Count (4.2)

$P = V_{rms} / N_p$ Floc-Particle Size (4.3)

The results determine the optimum for the taken raw water at a given pH. In order to determine the most effective concentration for the given raw water the slope of the Floc-Growth (equation 4.4) is defined as the Floc-Rate (equation 4.5). The magnitude of the Floc-rate is an indicator of the effectiveness of the related concentration. The higher the slope, the more efficient the concentration is.

$F_g = \sum P$ Floc-Growth (4.4)

$F_r = \delta P / \delta t$ Floc-Rate (4.5)

Traditionally, a jar test is used to determine the optimum coagulant dosage. A comparison between the results of a Jar Test and the Floc-Rate show a direct correlation between both methods.

These results confirm the effectiveness of the added concentration (50 mg/L). On full-scale, a coagulant concentration between 45 and 50 mg/L was adjusted, while the flocculation process was analyzed.

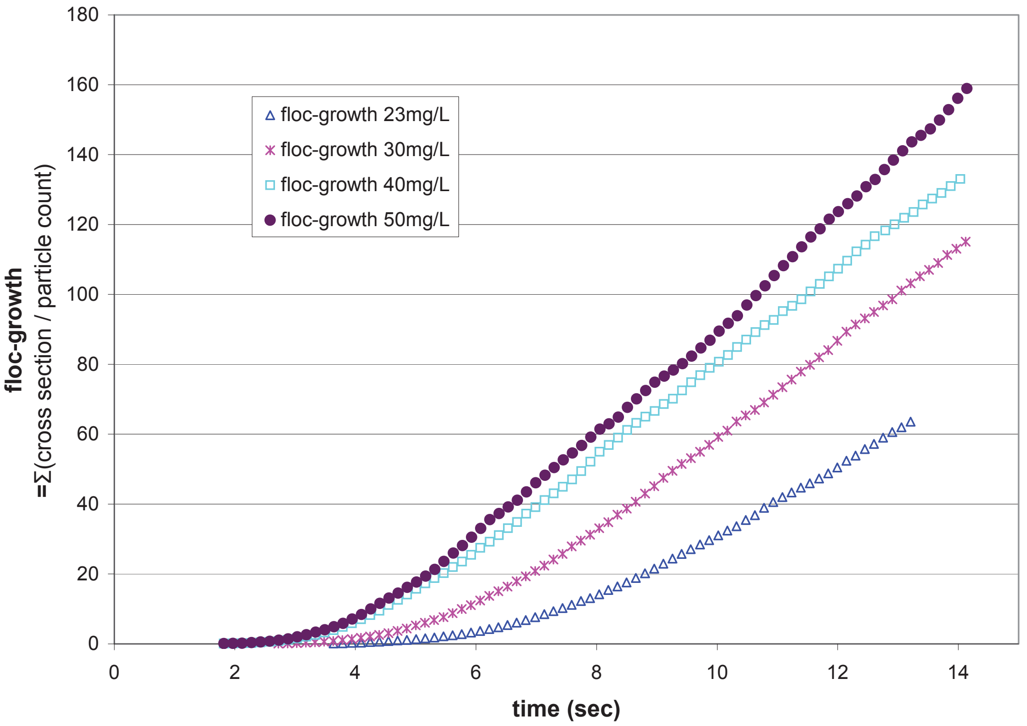


Figure 4.2: Floc-growth over time

3.1.2 Turbidity

The Interim Enhanced Surface Water Treatment Rule requires a turbidity value in treated water of 0.3 NTU. The GWTP is member of the partnership for safe water, established by AWWA (American Water Works Association) and therefore, aiming to reduce the turbidity to below 0.1 NTU in the treated water. Figure 4.3 shows the turbidity data from the GWTP.

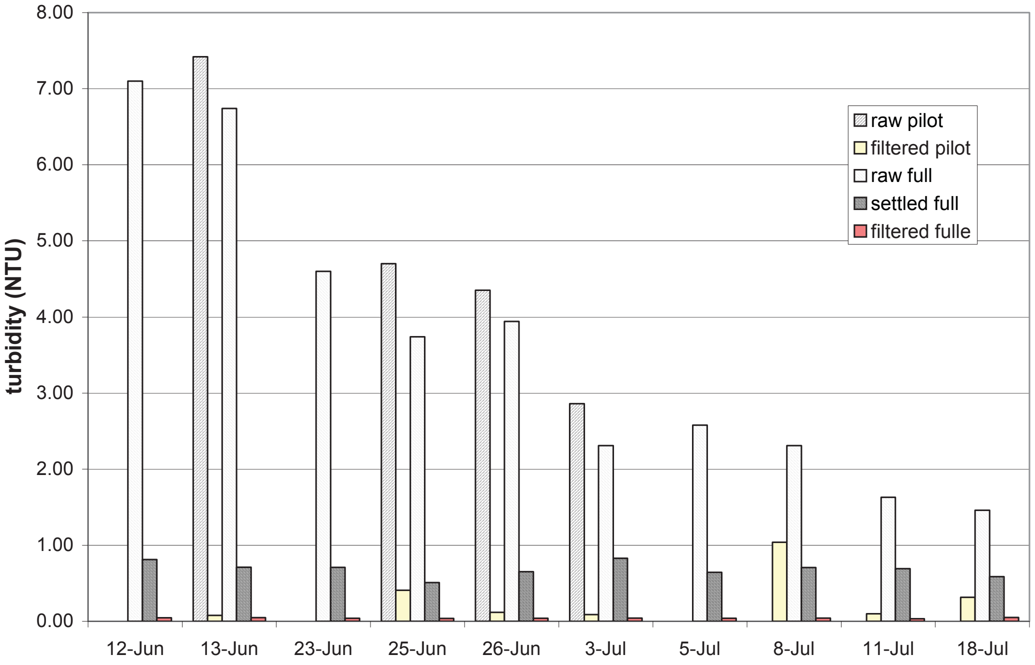


Figure 4.3: Turbidity removal on full-scale

After pre-clarification in the storage ponds on full-scale, an average NTU reduction of 76 % (standard deviation σ = 0.14) from the ponds to the settler effluent, and 98 % (σ = 0.010) throughout the whole treatment process in June and July 2003 was measured. The water after the filters never exceeded 0.051 NTU (average 0.04 / σ = 0.005). In the pilot-plant, the lowest turbidity values of the filtered water varied between 0.04 and 0.09 NTU during continuous operation over a couple of days. The performance of the plate settler was not satisfying, because an increase of the turbidity from the raw water to the settler effluent was determined with the laboratory turbidity meter (61 % / σ = 0.10). Frequent backwash (once per day) led to a 94.6 % turbidity reduction (σ = 0.03, determined with the laboratory turbidity meter).

3.1.3 Dissolved Organic Carbon (DOC)

The data in Figure 4.4 represent the fraction of the dissolved total organic carbon (TOC) in samples taken on full-scale and on pilot-scale.

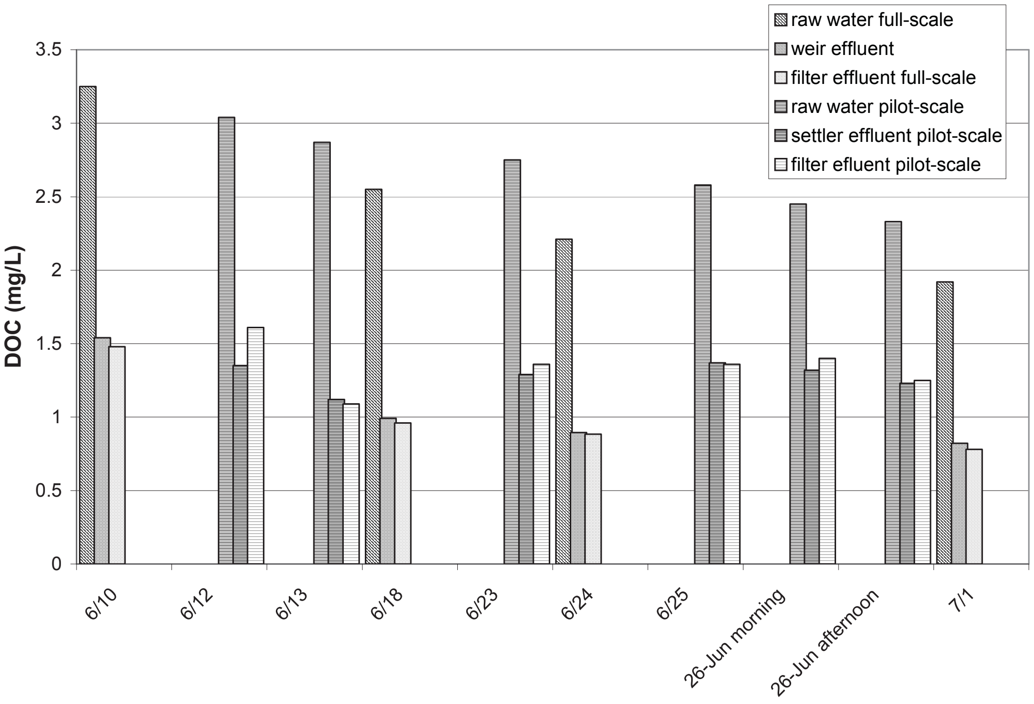


Figure 4.4: DOC removal on full-scale and on pilot-scale

Colloids, which pass through the 0.45 μm cellulose acetate filter during the sample preparation, are also included in the DOC values. Stage 1 DBPR requires a 35 % TOC-removal for Clear Creek water through enhanced coagulation. With a mean reduction of 57.6 % of DOC (standard deviation σ = 6.3) through the coagulation and flocculation process the full-scale plant easily achieves this goal. The pilot-plant shows high removal potential, with an average DOC-removal of 50.9% (σ = 7.4) for the month of June (Figure 4.5).

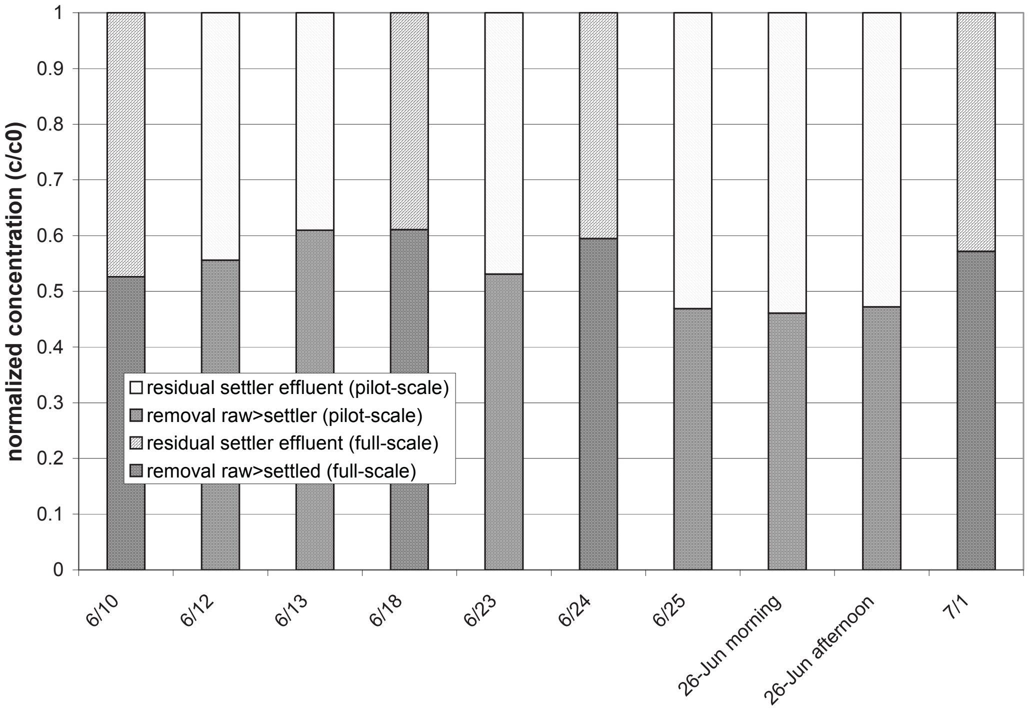


Figure 4.5: DOC removal from raw water to settler effluent on full-scale and on pilot-scale

Although the data show consistent DOC values in the raw water on full-scale (2.5 mg/L – σ = 0.57) and on pilot-scale (and 2,7 m/L – σ = 0.27), the pilot-plant shows DOC values, which are on average 7 % higher than on full-scale.

4.3 Removal Efficiency of Key Constituents

4.3.1 Specific Ultraviolet Absorption ($SUVA_{254}$)

The $SUVA_{254}$ value indicates the amount of unsaturated organic carbon compounds (primarily aromatic compounds) in a water sample. $SUVA_{254}$ indicates which fraction (hydrophobic or hydrophilic) predominates the NOM. According to the enhanced coagulation process, the $SUVA_{254}$ value gives sufficient information about the reduction of potential disinfecting byproduct predecessor substances.

The $SUVA_{254}$ data from the pilot-plant (Figure 4.6) confirm efficient removal of hydrophobic compounds during the study period (June 2003).

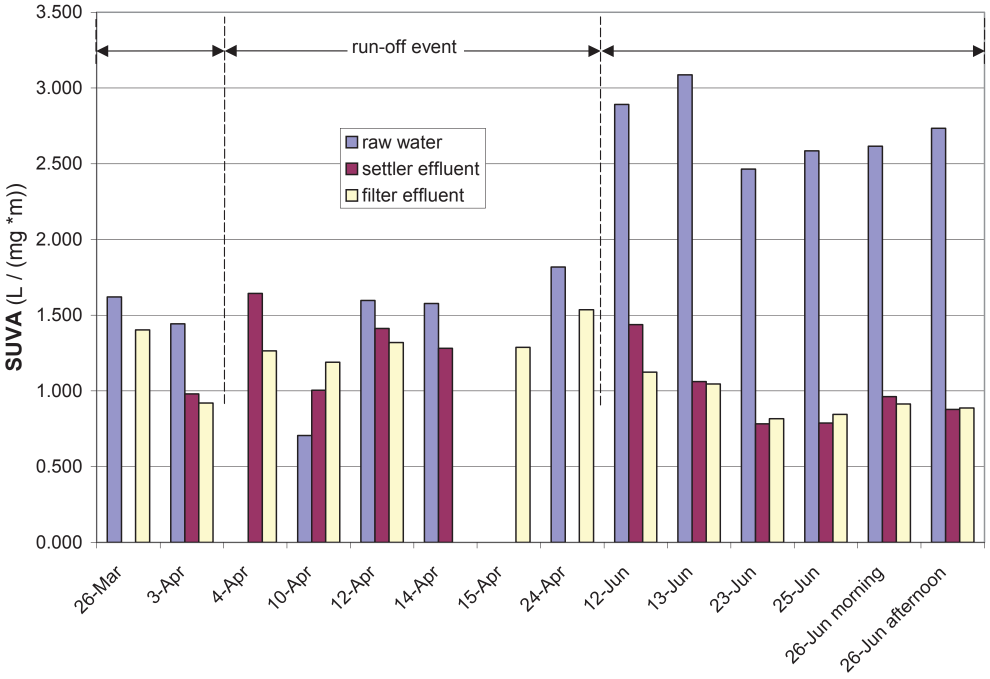


Figure 4.6: Specific Ultraviolet Absorption at 254 nm removal on pilot-scale

The water from a run-off event (April 4th) challenged the operation of the full-scale and the pilot-plant. Measurements during this time show unusual high DOC values, whereas the 10.9 mg/L from the 10th of April represents an outlier.

Pre run-off measurements show inconsistent DOC removal, which is related to performance and optimization problems during the startup phase of the pilot-plant. Samples taken in June show a more constant raw water quality. The average of the raw water $SUVA_{254}$ values in June are 2.7 L/(mg*m) with a standard deviation of $\sigma = 0.23$. These high values indicate a predominant hydrophobic fraction in the raw water. Throughout this period an average $SUVA_{254}$ reduction of 64.1 % ($\sigma = 7.1$, samples from 06/12 to 06/26) between the raw water and the settled water and 65.7 % ($\sigma = 2.4$) for the whole pilot-plant was determined. An average SUVA value of 0.895 L/(mg*m) ($\sigma = 0.12$) indicates a reduction of mainly hydrophobic constituents in the samples. Through the filter process no significant further DOC removal occurs. The filtration step, with anthracite and sand as filter media, removes mainly the particulate fraction of total organic carbon (TOC). The same fraction is removed through the filtration step during the sample preparation (0.45 μm cellulose acetate filter). The variation in the DOC values between settler effluent and filter effluent represents operational and sampling errors.

3.1.4 Manganese

Manganese removal was chosen as a key process parameter due to the reported high manganese concentration in the raw water (see 2.2.2). During the run-off event in April the manganese concentration reached unusually high values, greater than 0.9 mg/L (14th April). A seasonal variation in the manganese concentration can be observed, yet springtime values usually do not exceed 0.2 mg/L. The highest concentrations, approximately 0.7 mg/L, are usually observed in December and January.

In order to find an efficient oxidant concentration, several stoichiometric ratios (conc. KMnO4 / conc. Mn^{2+} in the raw water) were investigated (Figure 4.7).

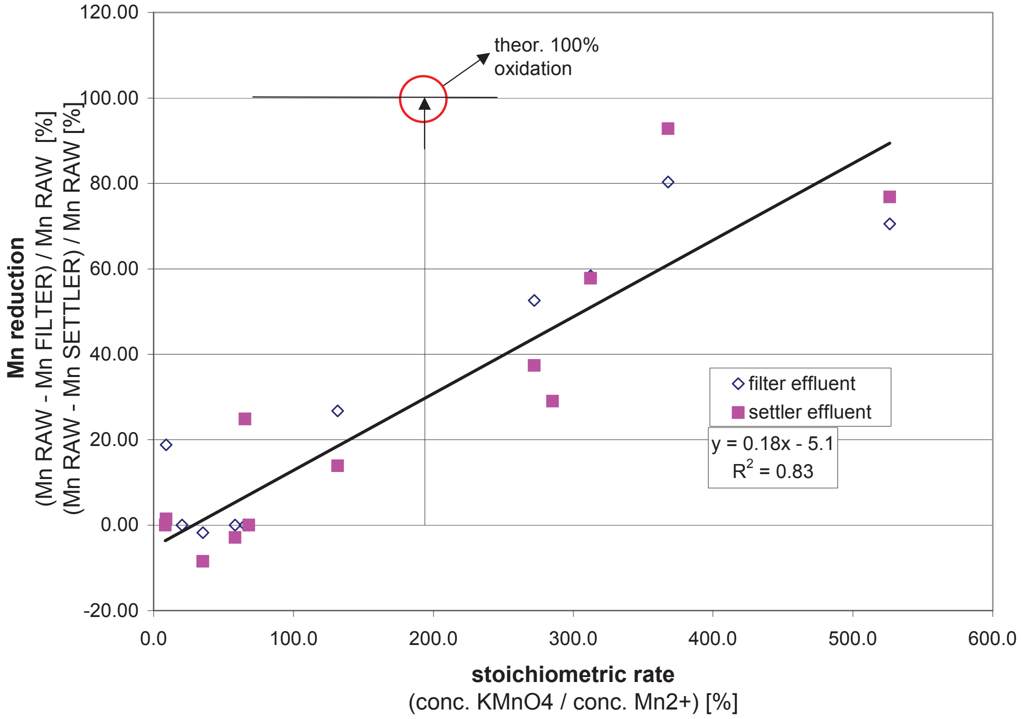


Figure 4.7: Manganese removal pilot-plant

The majority of the samples, taken after the run-off event in April reflect the seasonal average concentration of Mn^{2+} concentration in the raw water, which is 0.16 mg/L (σ = 0.028). According to the experimental results a 300 % ratio of $KMnO_4$ is necessary to achieve a 50 % reduction of initial Mn^{2+} concentration (500 % for a 80 % reduction). These results indicate a high oxidant demand of other raw water constituents like TOC, NOM or iron.

4.4 Process Control and Data Acquisition

The measured data are collected and stored in a Citadel database (National Instruments). The Citadel database compresses the data into binary files to save memory space (see appendix). The amount of stored data depends on the constancy of the measured data, which is defined by the bandwidth: the deadband. The deadband is a filter that eliminates noise in the received data. The value of each data point is compared to the previous value. Only if the difference between the new value and the previous value exceeds the deadband, the new value is stored. Besides the deadband, the conversion from the measured current signal to a display value (pH, flow rate, turbidity, temperature) is achieved with tags. A tag represents the connection between the database and the FieldPoint module.

The stored data can be monitored with the Operator SCADA-System, programmed for the pilot plant (see 3.1.7). In order to export the database to other programs the data are accessible trough the Historical Trend Viewer (HTV, National Instruments) or through Microsoft Query from Microsoft Excel. The HTV allows manipulating, monitoring, and exporting the stored data, and is implemented in the Measurement and Automation Explorer (National Instruments), which gives an overview of the whole National Instruments application, installed on the system. Each individual time interval between two data points can be extracted from the database, and the HTV module interpolates missing data points. Figure 4.8 and 4.9 show datasets of flow, pH and turbidity data exported into an excel spreadsheet from the Citadel database (time interval: 10 min). In order to demonstrate the capability of this module, a few key events and comments are added in the graphs. This allows a thorough investigation of the key data. Studying long-term behavior or trend analysis is much less time intensive with the HTV module than by study methods.

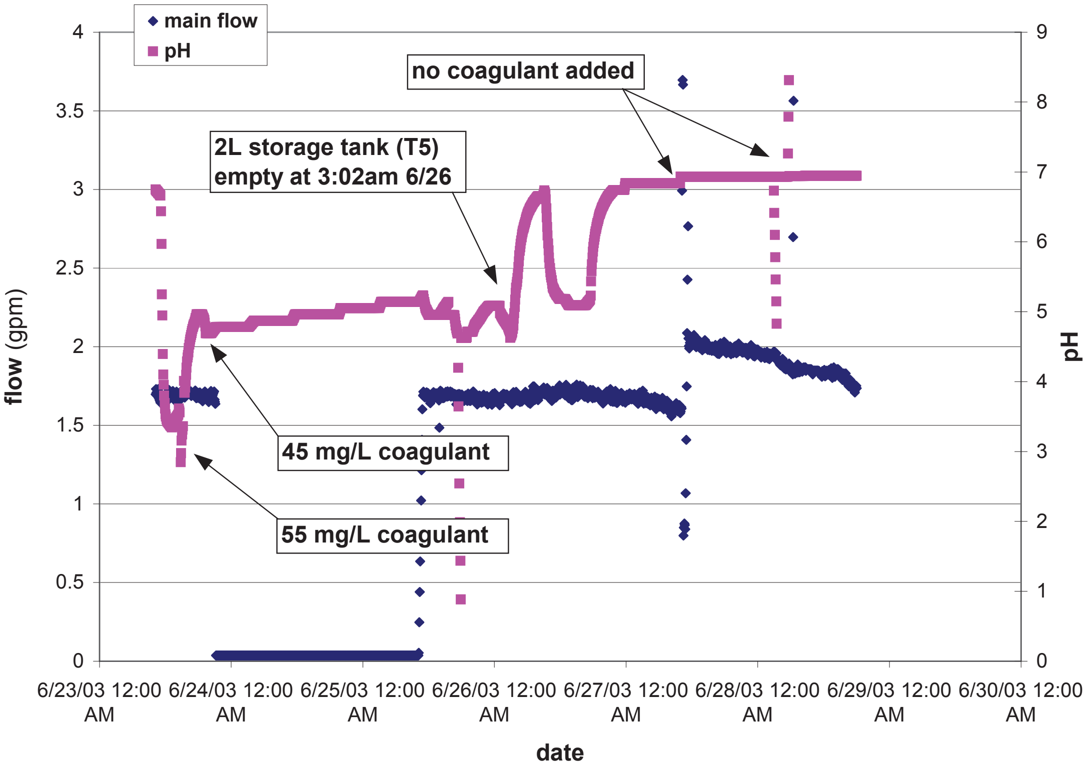


Figure 4.8: Flow and pH data (06/23 to 06/30) extracted from the Citadel database

Figure 4.8 shows an example-graph of flow and pH data, extracted from the Citadel database, as described before. Events, like changes of added concentration or operational failures (missing refill of tank T5) can be easily tracked and analyzed. Every individual time period can be analyzed.

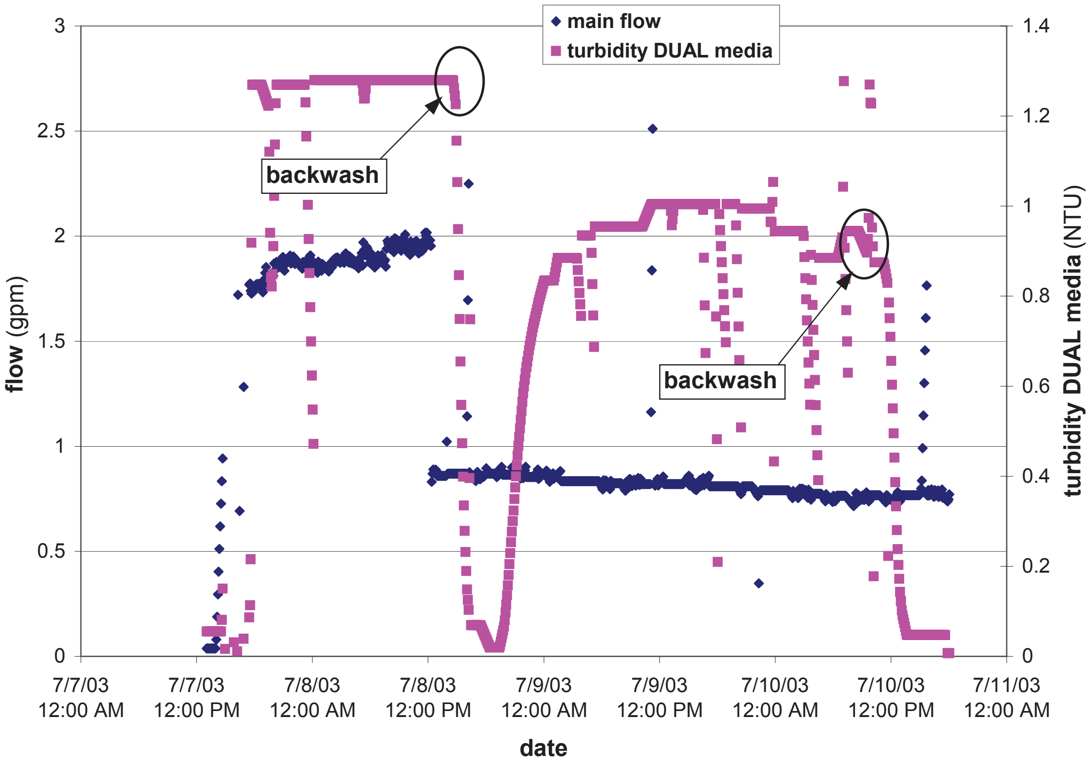


Figure 4.9: Flow and turbidity data (07/07 to 07/11) extracted from the Citadel database

Figure 4.9 shows an example-graph of flow and turbidity data. These graphs are capable for operational modifications on the filter column. Backwash intervals can be optimized by a turbidity evaluation after long-term experiments.

CHAPTER 5

CONCLUSION

The objective of this study was to simulate existing full-scale drinking water unit operations on pilot-scale. Necessary data points were defined in order to confirm the effectiveness and comparability of the pilot plant. The unit operations were combined and the performance of the pilot plant was improved and documented with tracer and baseline performance tests. $SUVA_{254}$ and manganese removal was investigated to determine the removal potential of these key constituents. A SCADA system was designed to collect / store data and to control the pilot plant.

Tracer tests were conducted to determine the hydraulic behavior of the installed unit operations on pilot-scale. Low t_{50}/τ values of the rapid mix chamber and the flocculation basin (0.77 and 0.48 respectively) and MDI values of 5.8 and 4.4 (respectively) indicate low mixing performance for both units. Baffles or different stirrer types could increase turbulence and improve the mixing. Additional research is necessary to investigate the mixing regime in further detail.

The conducted baseline tests determined the effectiveness of the coagulant and polymer concentration, which was related to the full-scale plant. The results from a real time flocculation analyzer (FlocAnalyzer from ClearCorp) confirmed that the same concentration added on pilot-scale, as on full-scale, is the most effective. An average DOC reduction of 50.9 % ($\sigma = 6.3$) for the coagulation / flocculation process and 49.8 % ($\sigma = 7.4$) for the whole treatment process including filtration respectively, confirms the similarity of the pilot and full-scale unit operations. During the month of June the GWTP removed 7.4 % more DOC than the pilot plant throughout the first treatment steps.

For the sedimentation process, a new concept was implemented with a plate settler based on a full-scale design. Turbidity measurements determined low performance of this unit process and the NTU-reduction of the full-scale counterpart could not be demonstrated on pilot-scale. The turbidity of the settler effluent was efficiently reduced with the dual media filter column to values below 0.1 NTU during continuous operation. Frequent backwash events were necessary to continuously reach this turbidity removal.

The $SUVA_{254}$ reduction indicates efficient removal of hydrophobic compounds. A mean reduction of 65.7 % ($\sigma = 2.4$) for the pilot plant, with average SUVA values of 2.7 L/(mg*m) ($\sigma = 0.23$) in the filtered water, was achieved. High oxidant demand of the raw water was determined by investigating the manganese reduction. To achieve a 50 % removal of the initial manganese concentration in raw water, a 300 % stoichiometric ratio was found to be necessary.

These findings confirm the capability of this pilot plant to simulate turbidity and TOC removal on downscaled unit operations employed on full-scale. As a result, the required regulations for full-scale are also met with this pilot plant. In order to improve the performance of each unit operation, further research is necessary. In combination with the designed SCADA system the pilot plant confirmed its capability for long-term investigations.

CHAPTER 6

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CHAPTER 7

APPENDIX

7.1 Module Summary SCADA System

3.1.1 Operator-SCADA System

The principle structure and function of this program module is described under chapter 3.1.7 (see figure 3.23). The Main menu, Plant overview, CoagSed, and Filtration front panels (Figure 3.23 a, b, c, and d) are based on a state machine architecture, which is an event driven architecture. Each event is programmed in the block diagram within a case structure and represents a certain user interaction on the front panel. To be more specific: by chancing a concentration, opening a valve, starting a pump, the related case structure is executed. The two main font panels CoagSed and Filtration have an initialization and an exit case-structure, where an external labVIEW module (Sub-VI) loads and saves the actual configurations and adjustments (Figure 7.1) in a file (specification see Table 7.1). This happens whenever one of these front panels is loaded or closed. After the initialize step the program stays in the wait case till the user makes any chances on the front panel. Every user interaction is recognized within the event-structure in the wait case. The event-structure opens each individual case. After a completed event (valve opened, pump started) the program returns to the wait case and waits for the next user input. Real time data are also read and updated in the wait case.

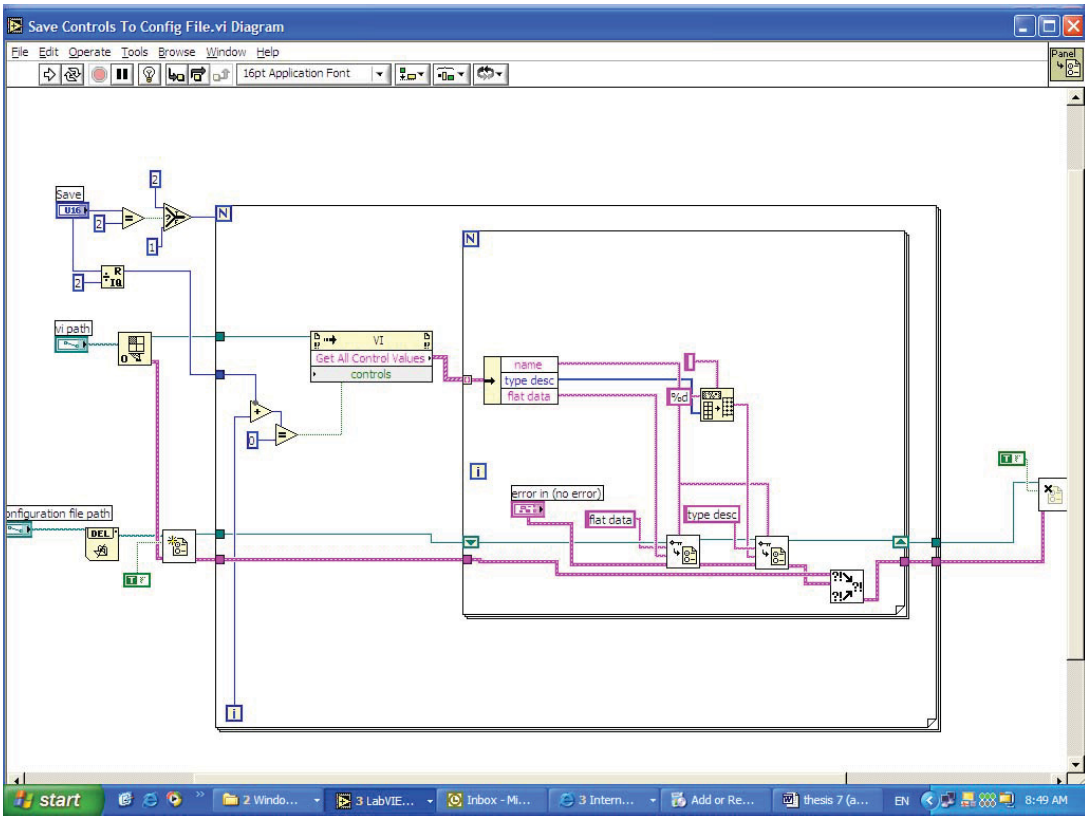

Figure 7.1: Save control to configuration file Sub-VI

Table 7.1 gives an overview of the designed sub Vi's and modules implemented in the operator-SCADA System.

Table 7.1: Programmed modules for Operator-SCADA System

Name	File name and Location on pilot plant terminal (c:\Program Files \ National Instruments \ LabVIEW 6.1 \ user.lib \ ..)	Description
IETL-Scada 0620	.. \ IETL-Waterplant \ IETL-SCADA 0620.vi	Main menu (Figure 3.22 a) / Login, SCADA and Data Acquisition module
Overall schematic		Front panel to chose CoagSed or Filtration front panel (Figure 3.22 b)
Flocculation 0620		CoagSed front panel (Figure 3.22 c)
Filter column 0616		Filtration front panel (Figure 3.22 d)

Table 7.1 cont.

Login		Verification front panel
Verify Information		Login information (username and password) stored in this file
Citadel Data Viewer 0619		Historic-data front panel (Figure 3.22 f)
Save Controls to Config File		Saves the control and indicator adjustment from the CoagSed and Filtration front panel, in a file by switching to another frontpanel
Load Controls From Config File		Loads the saved adjustments by opening the CoagSed and Filtration front panel, from the configuration file
Temp graph 0620		Actual-data front panel (Figure 3.22 e)
Temp-water		VI to measure and transform the water temperature (TR02) through FieldPoint module FP-AI-111
TempAmbient		VI to measure and transform the ambient temperature (TR01) through FieldPoint module FP-AI-111
flowrate		VI to measure and transform the main flow (FR01) through FieldPoint module FP-AI-111
Turbidity (GAC and DUAL)		VI to measure and transform the turbidity (QR02, QR03) through FieldPoint module FP-AI-111
pHfloc		VI to measure and transform the pH (QR01) through FieldPoint module FP-AI-111
Pump_CH0 (FlocAid) 0414		VI to control P3 through FieldPoint module FP-RLY-420 / 24V
Pump_CH1 (NaOH) 0414		VI to control P4 through FieldPoint module FP-RLY-420 / 24V
Pump_CH2 (coagulant) 0414		VI to control P5 through FieldPoint module FP-RLY-420 / 24V
Pump_CH3 (oxidation) 0414		VI to control P10 through FieldPoint module FP-RLY-420 / 24V

Table 7.1 cont.

M3_120V (CH0_GAC pump)		VI to control P9 through FieldPoint module FP-RLY-420 / 110V
M3_120V (CH1_V3_1)		VI to control valve V3.1 through FieldPoint module FP-RLY-420 / 110V
M3_120V (CH3_P8)		VI to control P8 through FieldPoint module FP-RLY-420 / 110V
M3_120V (CH6_V4_15)		VI to control V4.15 through FieldPoint module FP-RLY-420 / 110V
Cal-chem_feed 0609		Calculation of the delay time for P3, P4, P5, and P10

3.1.2 Web-SCADA System

Table 7.2: Programmed modules for Web-SCADA System

Name	File name and Location on pilot plant terminal (c:\Program Files \ National Instruments \ LabVIEW 6.1 \ user.lib \ ..)	Description
Web panel	.. \ IETL-Waterplant \ Web panel.vi	Web-SCADA-System front panel
Temp graph 0620		Actual-data front panel (Figure 3.22 e)
Temp-water		VI to measure and transform the water temperature (TR02) through FieldPoint module FP-AI-111
TempAmbient		VI to measure and transform the ambient temperature (TR01) through FieldPoint module FP-AI-111
flowrate		VI to measure and transform the main flow (FR01) through FieldPoint module FP-AI-111

Table 7.2 cont.

Turbidity (GAC and DUAL)		VI to measure and transform the turbidity (QR02, QR03) through FieldPoint module FP-AI-111
pHfloc		VI to measure and transform the pH (QR01) through FieldPoint module FP-AI-111

3.2 Measuring Data

Table 7.3: NTU-data for pilot-scale and full-scale

	raw water				settler effluent				filter effluent			
Date	full scale				full scale		pilot scale		full scale		pilot scale	
	NTU	NTU	NTU	NTU	NTU	NTU	NTU	NTU	NTU	NTU	NTU	
12-Jun	7.1	6.62			0.813	0.79			0.047	0.05		
	6.13				0.774				0.048			
13-Jun	6.74	6.50	7.42	7.31	0.711	0.71	22.20	22.06	0.048	0.05	0.08	0.09
	6.26		7.2		0.71		21.90		0.049		0.096	
23-Jun	4.6	4.62			0.708	0.71			0.041	0.04		
	4.63				0.707				0.035			
25-Jun	3.74	3.98	4.7	4.70	0.509	0.57	12.70	12.80	0.039	0.04	0.407	0.40
	4.22				0.626		12.90		0.039		0.391	
26-Jun	3.94	3.86	4.35	4.35	0.653	0.64	8.50	8.61	0.04	0.04	0.116	0.11
	3.77				0.636		8.71		0.039		0.102	
3-Jul	2.31	2.26	2.86	2.83	0.829	0.90	9.19	9.31	0.044	0.04	0.09	0.13
	2.21		2.79		0.969		9.43		0.036		0.162	
5-Jul	2.58	4.53			0.644	0.61			0.042	0.04		
	6.48				0.575				0.038			
8-Jul	2.31	2.07			0.705	0.77			0.044	0.04	1.04	1.04
	1.82				0.841				0.043			
11-Jul	1.63	1.65			0.692	0.69			0.034	0.04	0.1	0.10
	1.67				0.678				0.043			
18-Jul	1.46	1.37			0.586	0.60			0.052	0.05	0.316	0.32
	1.28				0.607				0.049			

Table 7.4: DOC-data for pilot-scale and full-scale

	raw water		settler effluent				filter effluent			
Date	full scale	pilot scale	full scale	delta DOC	pilot scale	delta DOC	full scale	delta DOC	pilot scale	delta DOC
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
6/10	3.25		1.54	1.71			1.48	0.06		
6/12		3.04			1.35	1.69			1.61	0.26
6/13		2.87			1.12	1.75			1.09	0.03
6/18	2.55		0.992	1.558			0.961	0.031		
6/23		2.75			1.29	1.46			1.36	0.07
6/24	2.21		0.895	1.315			0.885	0.01		
6/25		2.58			1.37	1.21			1.36	0.01
26-Jun morning		2.45			1.32	1.13			1.4	0.08
26-Jun afternoon		2.33			1.23	1.1			1.25	0.02
7/1	1.92		0.822	1.098			0.781	0.041		

Table 7.5: SUVA-data from pilot-scale

	raw water					settler effluent					filter effluent				
Date	UV	Avg. UV	TOC	Avg. TOC	SUVA	UV	Avg. UV	TOC	Avg.TOC	SUVA	UV	Avg. UV	TOC	Avg TOC	SUVA
	(1/5cm)	(1/5cm)	(mg/L)	(mg/L)	(L/mg m)	(1/5cm)	(1/5cm)	(mg/L)		(l/mg m)	(1/5cm)	(1/5cm)	(mg/L)	(mg/L)	(L/mg m)
26-Mar	0.217	0.2115	2.61	2.61	1.621	*2.57					0.111	0.113	1.61	1.61	1.404
	0.206										0.115				
3-Apr	0.198	0.2	2.52	2.77	1.444	0.128	0.1295	2.64	2.64	0.981	0.127	0.128	2.78	2.78	0.921
	0.202		3.02			0.131					0.129				
4-Apr	0.23	0.2265				0.152	0.152	1.85	1.85	1.643	0.149	0.1495	2.39	2.365	1.264
	0.223					0.152					0.15		2.34		
10-Apr	0.361	0.385	10.9	10.9	0.706	0.192	0.193	3.84	3.84	1.005	0.191	0.1945	3.27	3.27	1.190
	0.409					0.194					0.198				
12-Apr	0.237	0.238	2.98	2.98	1.597	0.198	0.188	2.66	2.66	1.414	0.186	0.1835	2.78	2.78	1.320
	0.239					0.178					0.181				
14-Apr	0.251	0.2525	3.2	3.2	1.578	0.163	0.1615	2.52	2.52	1.282					
	0.254					0.16									
15-Apr	0.289	0.2885									0.186	0.1835	2.85	2.85	1.288
	0.288										0.181				
24-Apr	0.302	0.301	3.31	3.31	1.819						0.22	0.222	2.89	2.89	1.536
	0.3										0.224				
12-Jun	0.44	0.4395	3.04	3.04	2.891	0.096	0.097	1.35	1.35	1.437	0.092	0.0905	1.61	1.61	1.124
	0.439					0.098					0.089				
13-Jun	0.438	0.443	2.87	2.87	3.087	0.058	0.0595	1.1	1.12	1.063	0.058	0.057	1.09	1.09	1.046
	0.448					0.061		1.14			0.056				
23-Jun	0.336	0.339	2.75	2.75	2.465	0.051	0.0505	1.29	1.29	0.783	0.054	0.0555	1.36	1.36	0.816
	0.342					0.05					0.057				
25-Jun	0.332	0.3335	2.58	2.58	2.585	0.053	0.054	1.37	1.37	0.788	0.055	0.0575	1.36	1.36	0.846
	0.335					0.055					0.06				
26-Jun morning	0.321	0.3205	2.45	2.45	2.616	0.064	0.0635	1.32	1.32	0.962	0.064	0.064	1.4	1.4	0.914
	0.32					0.063					0.064				
26-Jun afternoon	0.318	0.3185	2.33	2.33	2.734	0.055	0.054	1.23	1.23	0.878	0.054	0.0555	1.25	1.25	0.888
	0.319					0.053					0.057				

Table 7.6: Manganese removal pilot plant

	Raw Water		**Settler Effluent**		**Filter Effluent**	
Date	Mn	Avg. Mn	Mn	Avg. Mn	Mn	Avg. Mn
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
5-Jul	0.109	0.1075	0.13	0.129	0.203	0.202
	0.106		0.128		0.201	
8-Jul	0.165	0.1675	0.165	0.165	0.132	0.136
	0.17		0.165		0.14	
11-Jul	0.142	0.142	0.154	0.154	0.144	0.1445
					0.145	
18-Jul	0.153	0.153	0.115	0.115	0.015	0.015
19-Jul	0.147	0.147	0.18	0.18	0.17	0.17
7/21/2003 morning	0.172	0.172	0.177	0.177	0.076	0.076
7/21/2003 afternoon	0.187	0.187	0.161	0.161	0.137	0.137
7/22/2003 morning	0.192	0.192	0.081	0.081	0.08	0.08
7/22/2003 afternoon	0.19	0.19	0.044	0.044	0.056	0.056