Sustainable Surface Water Treatment Technology

Our goal is to create an integrated process model for a water treatment process train consisting of high Peclet number flocculation, floc blanket filtration, and plate settlers. The process model will be used to create optimized designs of sustainable, gravity-powered, robust drinking water treatment facilities. We hypothesize that

1) A model that describes geometric-growth of fractal floc particles at high-Peclet numbers (**E**nergy Dissipation, **F**ractal flocculation, **G**eometric growth, **H**igh Peclet number reactor--EFGH model) will serve as a rational basis for flocculator design (Weber-Shirk, 2009a).
2) Floc blankets that form during upflow of destabilized colloidal suspensions can be modeled as a combination of filtration (where influent colloids collide with flocs in the floc blanket and are captured) and flocculation (where influent flocs collide with each other and grow in size due to the energy dissipation resulting from passage through the floc blanket).
3) Modeling of plate settler performance can be based on the distribution of influent particle sedimentation velocities.
4) By systematically varying the independent parameters for each of the coupled unit processes in the flocculation/floc blanket/plate settler treatment train, we can develop performance curves and can test the validity of the predictions of each of the unit process models.
5) Holistic study of the entire treatment process will facilitate optimization of the individual unit processes as well as the optimization of the overall process. The coupled models will be tested at the laboratory and pilot plant scales, and then used to guide construction of AguaClara water treatment plants.
6) Robust, sustainable treatment designs developed and implemented in the global south will be applicable in industrialized nations as well.

In the following section we describe the magnitude of the global challenge to build, upgrade, and maintain water supply infrastructure. We identify the specific challenge of providing robust and sustainable drinking water treatment for towns and small cities. The AguaClara section, introduces the program at Cornell University that integrates undergraduate and graduate students, in a multidisciplinary team that is conducting research and creating designs for low-cost, high performance water treatment facilities. In the section on unit processes, we analyze their capabilities and explain how the AguaClara team selected hydraulic flocculation, floc blanket filtration, and plate settler sedimentation for optimization. The section on research challenges and program capabilities provides background on the 40 member student team and the laboratory, pilot, and full-scale facilities that will be used for this research program. Subsequent sections describe the EFGH flocculation model, floc blanket, and sedimentation research. We describe the international partners who build the AguaClara facilities and the team's commitment to knowledge dissemination and to open source engineering, and then summarize the Broader Impacts of the proposed research.

Global Water Supply Infrastructure

Globally, the infrastructure required to support human society is either grossly inadequate (as in the global south, the developing world) or rapidly becoming obsolete. Dividing the global infrastructure need between water, power, road and rail, and air and seaport sectors, the most expensive infrastructure sector is water with required projected spending of 1 trillion USD per year for the next 25 years (Figure 1) (Doshi, et al., 2007). An investment to develop more energy efficient, robust, and cost effective water treatment technologies could result in significant savings in this sector.

About 1 billion people worldwide lack access to improved water supplies. That figure underestimates the scale of the need since it is likely that another 1 billion have access to untreated piped water in their homes and thus technically have "improved" water (that is not safe to drink). Thus, the global need for safe drinking water may already exceed 2 billion, an estimate that does not include the additional demand that will be created by population growth over the coming decades.

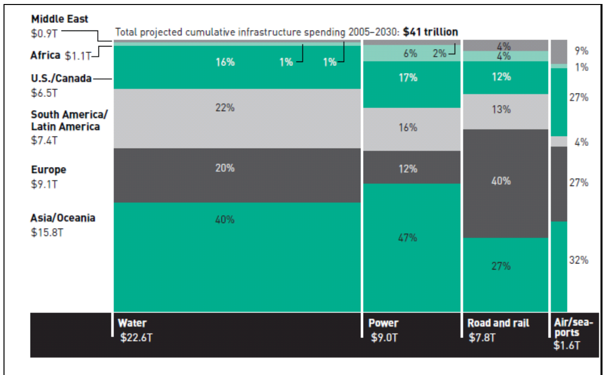

Figure 1. Projected total infrastructure investment needed during the next 25 years to modernize obsolescent systems and meet expanding demand (Doshi, et al., 2007).

Water treatment technologies address a broad range of water quality issues. One of the most common issues for surface waters is suspended solids that can be measured as turbidity. Removal of turbidity is important because the suspended solids include pathogens and because the suspended solids interfere with disinfection processes.

Statistics are lacking for the number of people who routinely drink turbid untreated surface waters. If we estimate that only ¼ of the 2 billion without safe water are using turbid surface waters, the population that needs surface water treatment would be 0.5 billion. The water treatment technology "space" can be characterized as a function of the number of people who can be served by a single facility and the maximum turbidity that the technology can treat (Figure 2). Approximately ¼ of the people who currently lack access to safe water live in towns and cities with populations between 1000 and 50,000. Thus, the intersection of the 0.5 billion people who are using untreated turbid surface waters and those who live in small cities yields 125 million individuals. If the average town size is 10,000, then 12,500 facilities need to be built in the next 10 years at a rate of more than 3 facilities per day. It isikely that 12,500 facilities is a low estimate since Pakistan alone recently committed to building 6,000 surface water treatment plants over the next 3 years (Anonymous, 2008).

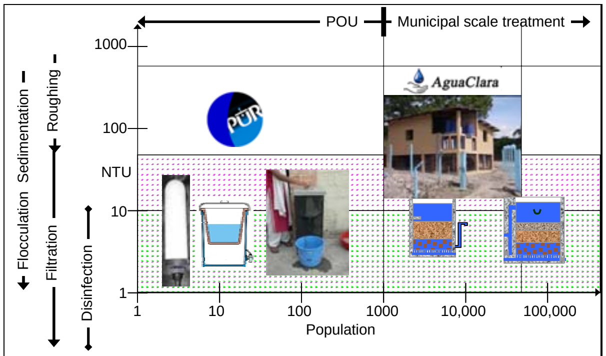

Figure 2. Water treatment technology space showing the need for a robust technology that can treat high turbidity surface waters for communities greater than 1000 people.

The constraints on water treatment technologies for small cities in the global south are significant. The electrical generating capacity is severely strained and the electrical grid experiences frequent outages (Doshi, et al., 2007). As a result, building water treatment facilities that rely on electric power guarantees that the technology will have a high failure rate. Treatment plant operators in the global south typically have limited or no formal education. Thus, best water treatment technologies are designed to allow the operator to visually monitor performance. Treatment plant components that can fail must be available in the local supply chain and any required fabrication must be accessible to the plant operator.

The performance in Honduras of conventional water treatment facilities that rely on electrically powered processes and require imported specialty components is abysmal. The

AguaClara team has visited eight facilities in Honduras and only one was reliably producing water with a turbidity < 1 Nephelometric Turbidity Unit (NTU). Most of the facilities were not reaching the 5 NTU value for customer acceptability set by the World Health Organization, 2006). Some of the facilities were abandoned. The high failure rate of imported, mechanized, high tech, treatment facilities makes it clear that a more robust alternative is needed. The Cornell University AguaClara project was founded in 2005 to address this need.

AguaClara

AguaClara is a project in the School of Civil and Environmental Engineering at Cornell University that is improving drinking water quality through innovative research, knowledge transfer, open source engineering and design of sustainable, replicable water treatment systems. Over the past 4 years, the team has steadily grown to its current size of 40 students. This semester the team includes 5 Master of Engineering, 2 Master of Science, 1 Ph.D., and over 30 undergraduate students. Student members are divided into teams that work on research, design, public relations, and fundraising. Research is by far the largest component with teams working on characterization of optimal energy dissipation rates in hydraulic flocculation, floc blanket filtration, optimization of plate settler geometry, development of methods to remove over-saturated gases that cause floating flocs, and testing of a robust non-electric controller that maintains correct chemical dosages during plant flow rate changes.

AguaClara is not only a major research and design team that incorporates graduate and undergraduate students, it also includes long term collaboration with our principle implementation partner, Agua Para el Pueblo (APP) in Honduras. This collaboration includes 2 full time AguaClara Engineers–Cornell University graduates who had worked on the AguaClara team and are currently employees of APP–serving as intermediaries between the AguaClara team at Cornell and APP staff. An APP civil engineer provides structural design and construction supervision for the AguaClara plant construction. A technician provides training and assistance to plant operators and helps identify Honduran communities that need safe water and meet the requirements for an AguaClara facility.

The AguaClara team has developed a gravity-powered, nonelectric water treatment process that incorporates a calibrated flow controller (Weber-Shirk, 2009b) for chemical dosing, hydraulic flocculation, and high-rate upflow sedimentation. As of February 2009, 5 municipal water treatment plants that serve over 15,000 customers have been built in Honduras using AguaClara technologies (Figure 3). Over the past 4 years, the AguaClara team has been conducting laboratory research and creating design algorithms that make it possible for the team to deliver highly detailed 3-D drawings to our partners who are building the facilities. Recognizing that the engineering costs for the design of 3 water treatment plants per day for the next 10 years would be prohibitive if each facility were custom designed, the AguaClara team has committed to providing open source designs using a web-based design tool. Our commitment to open source engineering means that all of the design assumptions and algorithms used will be open for review. We anticipate having many implementation partners using these designs as the technology spreads.

Figure 3. AguaClara water treatment plant in Ojojona Honduras.

The AguaClara team began creating tools to automate the design process in the spring of 2006. The design tool is written in MathCAD which provides automatic dimensional checking to eliminate the risk of unit errors. The design tool consists of an integrated set of design algorithms that make it possible to create a detailed hydraulic and reactor design for an AguaClara water treatment plant. The power of the tool is that it is able to specify all of the plant dimensions AND it is able to create the set of text commands required by AutoCAD to create a detailed 3-D drawing of the plant (Figure 4). Our plan is to create an online client server implementation of this design tool that will make it possible for anyone with internet access to provide plant specifications (flow rate, details on preferred sedimentation tank configuration, optimal tank widths based on local materials, etc.) and then receive an email from the server containing detailed plant specifications and the AutoCAD drawing. Our challenge will be to provide training through implementation partners to new contractors, nongovernmental organizations, and government agencies so that they can use the design tool and can learn the construction techniques to build the facilities. The goal is to empower many local organizations to build the facilities.

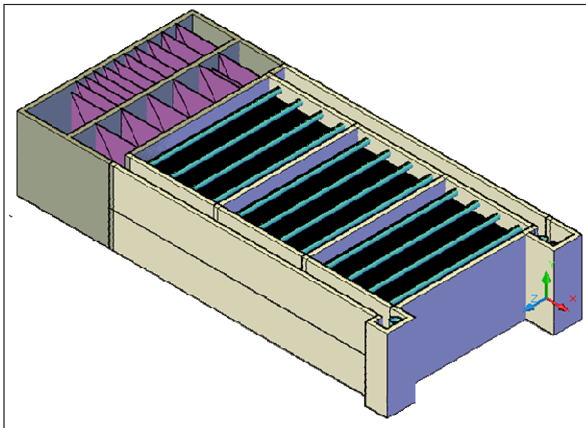

Figure 4. AutoCAD rendering of an AguaClara water treatment plant. The model was created using the automated design tool.

It is our expectation that open access to knowledge will revolutionize the water treatment sector. The reliance on poorly performing patented technologies in the global south will no longer be necessary. Perhaps most importantly, the AguaClara team will be able to continue to incorporate feedback gained from full scale facilities and thus continually improve the designs that are provided. This iterative design process has already resulted in significant new insights into optimal design of flocculators and sedimentation tanks. APP has challenged us to create designs that reduce capital costs below the current $20/person served. On a flow capacity basis, the total cost for an AguaClara water treatment plant is approximately $5000 per L/s of capacity. This cost includes community selection, design, build, initial operation, operator training, and transfer to the community. In stark contrast, the capital cost for the Croton filtration plant in New York City is approximately $200,000 per L/s of capacity.

Many of the current water treatment facilities built using concrete tanks are designed and constructed as if they were the first and last water treatment plant that was needed. Design errors are common and both package plants and built-in-place facilities frequently include serious mistakes that adversely affect performance including: hydraulic design errors, plant layouts that make it difficult for the operator to monitor performance, and lack of easy monitoring of raw water and chemical flow rates. Existing imported package plants in Honduras have hydraulic designs that break up flocs between the flocculation tank and the sedimentation tank and require plant operators to slide through body hugging ports to clean the units. The package plant reliance on automation and mechanical components with a short lifetime requires a supply chain for mechanical components, and the plants work on a continual basis only if the electrical grid is reliable. These package plants show little or no evidence of evolution to a robust, sustainable design.

The AguaClara team recognizes the importance of five essential components:

1) Sustainability that emphasizes community empowerment and pride of ownership.

2) A learning cycle of research, design, build, operate, train, transfer, evaluate, repeat.
3) Creation of dimensionally correct design algorithms in an open source integrated design tool.
4) A research program to develop new insights into the physical and chemical processes of flocculation and sedimentation.
5) A training program to teach the new insights to students and to partner organizations.

Empowerment is a key component of water treatment plant sustainability. If the plant operator does not have the resources or the training to fix components that fail, then the plant will fail. AguaClara designs rely on locally available materials, indigenous construction techniques, and community labor to ensure that any failures can be readily addressed locally.

The learning cycle continues to be an incredibly rich experience for Cornell students and for our partners and communities in Honduras. We have a very efficient cycle that makes it possible to go from final design to plant operation in less than 6 months. Our latest plant went through the final design process in late fall of 2008 and will be coming on line in early March of 2009. This makes it possible to evolve the plant designs quickly and for students to get excellent experience coupling research and development with prototyping, design review, and plant performance monitoring.

Unit Process Selection

AguaClara water treatment plants currently incorporate 3 serial unit processes (flocculation, plate settlers, and disinfection) and we are in the process of testing the inclusion of a floc blanket filter. Our choice of processes is unconventional, but is based on an analysis of the capabilities of the available processes, and in particular, the need for a robust, cost effective design. Based on the ability of flocculation and sedimentation to produce water that is clean enough to achieve effective disinfection (Figure 2), we have selected flocculation, sedimentation, and disinfection as core technologies. It is conventional wisdom that if the water is turbid, then it should be filtered. However, filtration is not a viable treatment technology for the highly turbid surface waters that are common in the mountainous terrain of Honduras. A review of the available technologies for turbidity removal reveals that flocculation and sedimentation can easily produce water with turbidity less than 5 NTU. Filtration processes can be used to treat water that is occasionally as turbid as 50 NTU, but rapid clogging makes them ineffective for continual use. Very turbid waters, above 50 NTU, can only be treated by the combination of flocculation and sedimentation or by multistage filtration. Thus, the limited ability of sand filters to handle turbid water suggests that the key processes for handling very turbid waters are flocculation and sedimentation. The significant insight here is that the flocculation/sedimentation processes can produce water that is clean enough that disinfection processes can be effective. Disinfection processes are effective for low turbidity waters (LeChevallier, et al., 1981) and a chlorine residual can be maintained with turbidities less than approximately 10 NTU.

The exclusion of sand filtration in AguaClara designs is perhaps surprising, but the high capital costs and large level land area requirements for slow sand filtration make it unaffordable for most communities in Honduras. The backwash requirements for rapid sand filters force a choice between pumps, with their reliance on electricity, or sufficient filter units with deep filter boxes for gravity powered backwashing. The need for approximately 6 filter boxes with all of the associated controls makes even the gravity backwashing option too expensive for many communities. We are well aware that multiple barriers are important in water treatment and that filtration should ideally be used to provide further protection. However, economic and infrastructure constraints in the global south limit viable options for a sustainable supply of safe water. Water treated to < 5 NTU through flocculation and sedimentation, and then chlorinated, is a viable and sustainable option. AguaClara facilities are sited so that a future filtration unit could be placed between the sedimentation and distribution tanks should resources become available for this addition to the process train.

Research Challenge and Program Capabilities

Over 60% of the current AguaClara team is focused on research. The research focus has evolved out of a need to develop solutions to a series of critical design issues. Several of these design issues arise because of the lack of cheap, reliable electric power. Other design issues are the result of a need to design high performing facilities without relying on filtration. The AguaClara team has, in effect, had to reinvent many of the components needed for water treatment.

1) Gravity powered flow controllers were designed for dosing aluminum sulfate and calcium hypochlorite (Figure 5) (Weber-Shirk, 2009b).
2) Easily fabricated linear flow measurement devices have been adapted from the Sutro weir (Figure 6).
3) The flow controller and flow measurement are currently being linked using a simple lever system to make it possible for the plant operator to select a chemical dose according to raw water turbidity, and that dose stays constant even if the plant flow rate changes.
4) Hydraulic flocculation designs have been created that account for the non-uniform energy-dissipation rate in the flocculator.
5) Design of a sedimentation tank inlet manifold incorporates a full hydraulic analysis of the flow distribution between ports.
6) Sedimentation tank inlet manifold port design prevents floc breakup by accounting for the high energy dissipation rate in the jet that forms after the *vena contracta*.
7) Vertical flow sedimentation tanks that incorporate floc blankets and plate settlers are being tested.

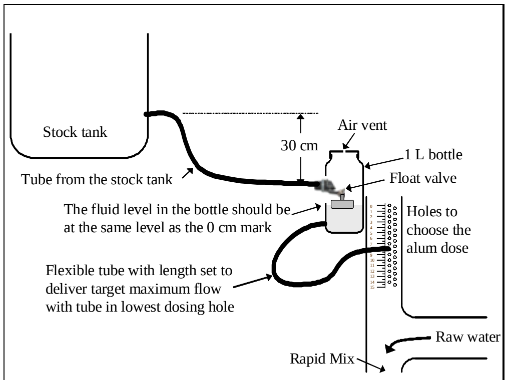

Figure 5. Flow controller installed to deliver alum at an AguaClara facility.

Figure 6. Linear flow orifice meter used to measure plant flow rate.

The AguaClara team has already demonstrated that open source designs incorporating feedback from facilities in operation can produce water treatment facilities that perform better than conventional designs in Honduras. The goal of this proposal is to enable the AguaClara team to further optimize the design of the flocculation/floc-blanket filtration/plate-settler sedimentation unit processes, based on a fundamental understanding of each unit process and the interactions between the unit processes. The primary goal of this proposal is to develop a fundamental understanding of each of the unit processes, and to link that understanding with models of the treatment process.

The proposed research will continue the effort by Cornell students to perform experiments that characterize the performance of the unit processes. Cornell's Environmental research laboratories are equipped with automated process-control capabilities (Weber-Shirk, 2008) that make it possible for undergraduate students with tight schedules to set up, automate, program, and run significant experiments. Automated control facilitates parametric tests by allowing programmed incremental changes in flow rates, raw water turbidities, or any of a series of computer controlled parameters. Currently the lab setups include a tube flocculator (Figure 7) equipped with a recently invented Flocculation Residual Turbidity Analyzer (FreTA), a sand filtration unit (Figure 8), a floc blanket research apparatus (Figure 9), and a plate settler research apparatus (Figure 10). The plate settler and floc blanket research set-ups include tube flocculators, floc blankets, and plate settlers, because it is necessary to characterize the performance of each unit process using an appropriate suspension of particles.

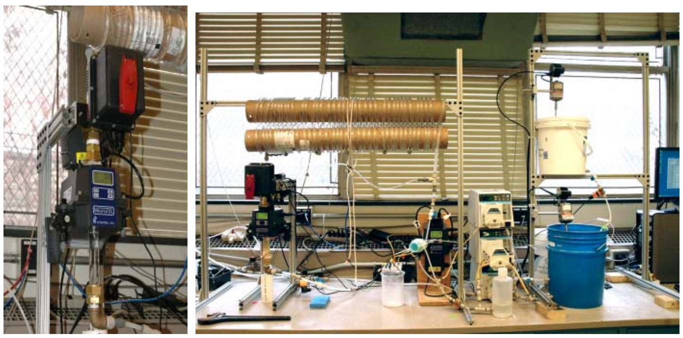

Figure 7. Automated raw water turbidity controller, alum feed, and tube flocculator (right) connected to the Flocculation Residual Turbidity Analyzer (FReTA) (close up on left).

Figure 8. Sand filtration unit with backwash pretreatment and direct filtration capabilities.

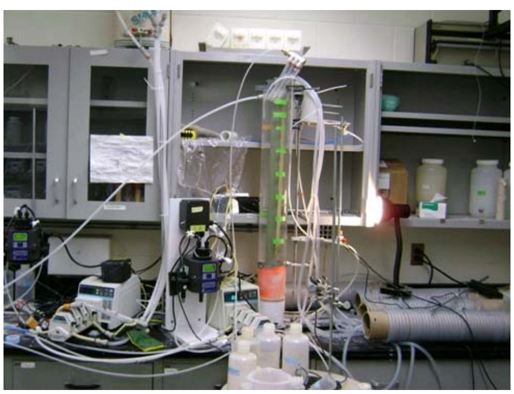

Figure 9. Floc blanket research apparatus.

Figure 10. Plate settler geometry research apparatus.

EFGH Flocculation Model

Flocculation is a well established water treatment technology and thus there is legitimate question about the utility of further investigation. However, there is very little research on flocculation in high-Peclet-number reactors where the flocs are expected to have a relatively narrow size distribution. These conditions are expected in hydraulic flocculators, where the energy dissipation (resulting from fluid flow through the reactor geometry) is responsible for particle transport and collisions. High-Peclet-number hydraulic reactors are more energy efficient. They do not have the short circuiting that is responsible for inadequately flocculated colloids in the effluent of low-Peclet-number reactors. Simplicity of construction and nonelectric operation make hydraulic flocculators the only viable option in many settings in the global south..

We have developed a fully analytical flocculation model, the EFGH model, which accounts for initial floc volume fraction, fractal dimension of flocs, and the corresponding changes in floc density and floc volume fraction as the flocs grow in size (Weber-Shirk, 2009a). The EFGH model is based on dimensional analysis of the physics of floc transport and aggregation and assumes geometric growth from collisions between similarly sized flocs. The diameter of a floc after *i* collisions is given by:

$$d_i = d_0 2^{\frac{i}{D_{Fractal}}} \quad (1)$$

where the number of primary particles in a floc is 2^i, d_0 is the size of the primary particles, and $D_{Fractal}$ is the fractal dimension. The fractal dimension of flocs is a critical parameter in the EFGH model. Meakin (1988) determined that flocs with 2 contact points have a fractal dimension of 2.13 and that flocs with 3 contact points have a fractal dimension of 2.19. Lambert et al., (2003) found that the fractal dimension values of *E. coli* flocs are in the range 1.9–2.20. Li and Ganczarczyk (1989) analyzed fractal dimensions of aggregates based on reported settling tests and size-density relationships and reported a fractal dimension of 2.3 for alum aggregates. Thus the fractal dimension for alum–clay flocs is expected to be between 2.1 and 2.3.

Given a fractal dimension of 2.3, the EFGH model accurately predicts floc densities.

$$\rho_{Floc_i} = \left(\rho_{Floc_0} - \rho_{H_2O}\right) 2^{\left(1-\frac{3}{D_{Fractal}}\right)i} + \rho_{H_2O} \quad (2)$$

where ρ_{Floc_i}, is the density of the floc after *i* collisions, ρ_{Floc_0} is the density of the primary particles at the beginning of the flocculator, and ρ_{H_2O} is the density of water. The terminal velocity of the floc after *i* collisions is given by:

$$V_{t_i} = \frac{g}{18\Phi} \frac{d_0^{\,2}}{\nu} \left(\frac{\rho_{Floc_0}}{\rho_{H_2O}} - 1 \right) 2^{\left(1-\frac{1}{D_{Fractal}}\right)i} \quad (3)$$

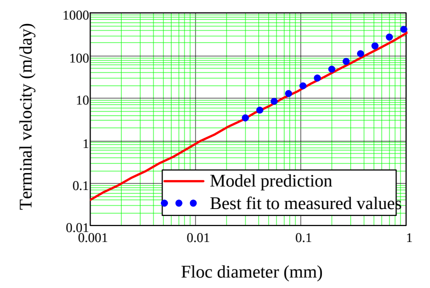

Figure 11. EFGH model for terminal velocity as a function of floc diameter.

where Φ is a shape and porosity correction factor (Tambo and Watanabe, 1979). The EFGH Model's predicted terminal settling velocities using equation 3 are shown in Figure 11. The primary particle density was based on a concentration of clay equal to 50 mg/L and an alum concentration equal to 40 mg/L to match the conditions for the data from Adachi (dashed line) (Adachi and Tanaka, 1997).

There has been a debate in the literature about which parameters adequately describe the particle collision rate (Cleasby, 1984, Clark, 1985, Han and Lawler, 1992). In the case of laminar flow, the analysis is relatively straightforward and the use of velocity gradients continues to be a useful factor in estimating collision potential (Pedocchi and Piedra-Cueva, 2005). Extension to turbulent flow conditions is more complex, and, in particular, the role of viscosity depends on the separation distance between particles and the intensity of the turbulence. In our work we will emphasize the more fundamental parameter of the energy dissipation rate, especially in the region of the flocculator where the particle separation distance exceeds the Kolmogorov microscale.

The EFGH flocculation model provides estimates of required time for particle collisions as a function of floc diameter and the initial floc volume fraction, ϕ_0. The model predicts collision times between similarly sized flocs based on a clearance rate that is dependent on whether the floc separation distance is in the viscous or inertial subrange as determined by the Kolmogorov length scale, η_K.

$$\eta_K = \left(\frac{\nu^3}{\varepsilon}\right)^{\frac{1}{4}} \tag{4}$$

where ν is the kinematic viscosity of water, and ε is the energy dissipation rate. The collision time, t_{c_i}, for flocs formed from *i* collisions in the viscous subrange, is given by

$$t_{c_i} \cong \frac{2}{3}\left(\frac{6}{\pi}\right)^{\frac{1}{3}} \phi_0^{\frac{-2}{3}} \left(\frac{\nu}{\varepsilon}\right)^{\frac{1}{2}} 2^{\left(\frac{2}{3}-\frac{2}{D_{Fractal}}\right)i} \tag{5}$$

In the inertial subrange, the corresponding equation is

$$t_{c_i} \cong \frac{2}{3}\left(\frac{6}{\pi}\right)^{\frac{1}{9}} \phi_0^{\frac{-8}{9}} \left(\frac{d_0^2}{\varepsilon}\right)^{\frac{1}{3}} 2^{\left(\frac{8}{9}-\frac{2}{D_{Fractal}}\right)i} \tag{6}$$

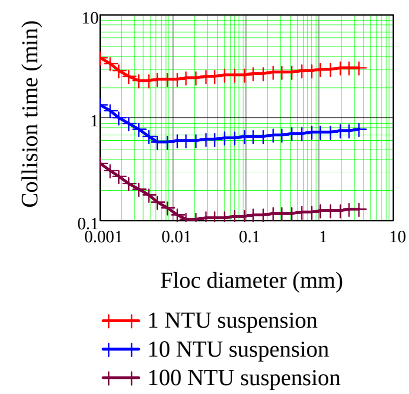

Figure 12. Predicted floc collision times for three suspensions at an energy dissipation rate of 1 mW/kg.

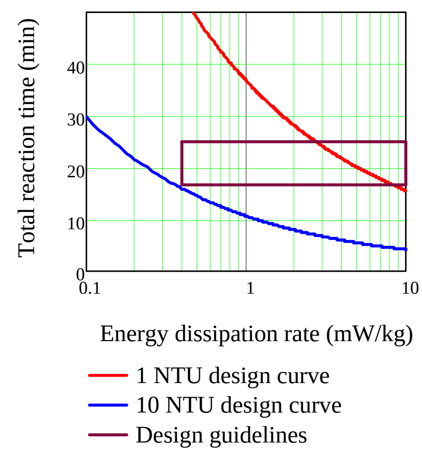

Figure 13. Model predicted total hydraulic flocculation times for two suspensions compared with design guidelines for hydraulic flocculators.

The EFGH model predictions, based on equations 5 and 6 for three raw water turbidities, are shown in Figure 12. The model predicts that the collision time decreases rapidly as the floc grows in the viscous subrange, and then remains relatively constant in the inertial subrange. The model also predicts a strong dependency on the floc volume fraction and explains the difficulty of flocculating low turbidity suspensions. The summation of the collision times required to grow a floc to a size that has a sedimentation velocity equal to the capture velocity of the subsequent sedimentation tank can be used to estimate the total flocculation time. The minimum flocculation time required to produce flocs with a sedimentation velocity of 10 m/day (the capture velocity used in AguaClara sedimentation tanks) is plotted as a function of the energy dissipation rate and suspension turbidity (Figure 13). The model's predictions are based on the fundamental physics of the flocculation process and do not include any fitting factors. The agreement between hydraulic flocculators design recommendations (Schulz, 1984) and the EFGH model is reasonable. High energy dissipation rates or large reactors will be necessary to meet the goal of treating low turbidity suspensions. The dramatic effect of the initial floc volume fraction reveals the importance of developing performance curves for water treatment unit processes. If suspensions with turbidities lower than 10 NTU can be handled by rapid sand filters, then it isn't as important to create flocs that can be captured by the sedimentation tank for low turbidity suspensions. For AguaClara facilities without filtration and with a treatment goal of 1 NTU, it is necessary to flocculate raw water with a turbidity greater than 1 NTU. This suggests that eliminating filtration in a treatment train requires a compensating increase in the flocculator residence time.

The relationship between raw water suspension properties and the required total flocculation potential as measured by the product of the average velocity gradient, G, and the reactor residence time, θ, can be used to describe laminar flow hydraulic flocculation.

$$G\theta \cong \frac{2}{3}\left(\frac{6}{\pi}\right)^{\frac{1}{3}} \phi_0^{\frac{-2}{3}} \sum_{i=0}^{n-1} 2^{\left(\frac{2}{3}-\frac{2}{D_{Fractal}}\right)i} \qquad (7)$$

where *n* is the number of sequential collisions required to produce a floc of the target diameter. Equations 3 and 7 were used to create predictions of the floc sedimentation velocities as a function of Gθ and the initial suspension (Figure 14). These laminar flow predictions will be tested using laminar flow tube flocculators. We will also use the model to make predictions for turbulent flow hydraulic flocculators and will test those predictions both at our 100 L/min pilot scale test facility that is located at the Cornell University Water Filtration Plant and at our full scale facilities in Honduras.

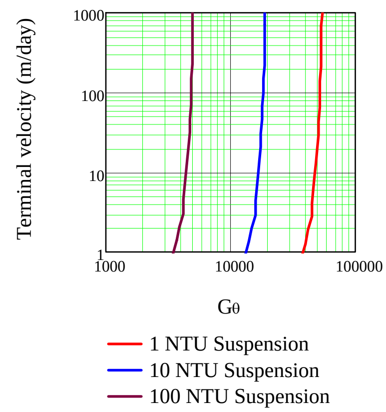

Figure 14. Model predicted terminal velocity of the flocculated suspensions as a function of Gθ and the initial suspension.

Connecting the EFGH model to performance predictions in turbulent flow hydraulic flocculators will require computational fluid dynamic (CFD) analysis of the spatial distribution of the energy dissipation rate. One of the AguaClara research teams is working to characterize the energy dissipation zone (Figure 15) using FLUENT. The results of this effort will make it possible to optimize the reactor geometry and to relate the performance of laminar flow flocculators to the performance of full-scale hydraulic flocculators. Using CFD it is possible to compute the flocculation potential of each finite element in the CFD grid, and thus account for the non-uniform distribution of the energy dissipation rate. The importance of geometry is illustrated in Figure 15 where a tall and slender reactor is shown to have large zones with insignificant energy dissipation, and hence ineffective flocculation.

Using the EFGH model to predict performance in a treatment train that also includes a floc blanket and plate settlers will require analytical or experimental characterization of the particle size distribution. This characterization is essential because the particles that have sedimentation velocities smaller than the capture velocity of the sedimentation tank cause residual turbidity in treated water.

Recent AguaClara graduate research has resulted in development of a research apparatus dubbed FReTA (for Flocculation Residual Turbidity Analyzer) designed to characterize floc particle size distributions through observation of temporal changes in turbidity in a quiescent settling column (Figure 7). FReTA is used downstream from a laminar flow tube flocculator that, under computer control, can systematically vary reaction time and energy dissipation rates that control floc formation.

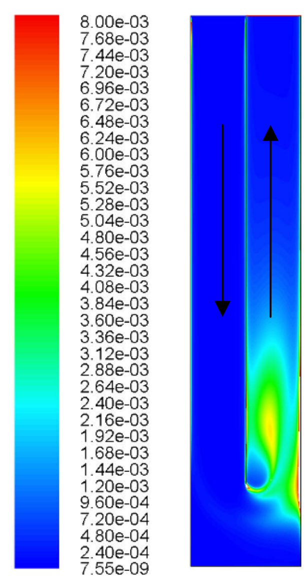

Figure 15. Energy dissipation rate in m^2/s^3 for a velocity of 0.1 m/s with a baffle spacing of 0.1 m. The length of the dissipation zone is approximately twice as long as the baffle spacing.

Floc Blanket

Floc blankets in upflow clarifiers can be thought of as a synthesis of flocculators and filtration units. The floc blanket apparatus (Figure 9) is providing data suggesting that turbidities below 1 NTU should be easily attainable even without sand filtration (Figure 17). We have shown (data not included here) that a treatment train containing flocculation/floc blanket/plate settlers can produce very low turbidity effluent if it includes excellent flocculation before the floc blanket. This is because a floc blanket does not provide sufficient collision opportunities to have all of the primary particles grow to a size that can be captured in the plate settlers. The floc blanket performance reported as pC* (p is the negative $\log_{10}$, and C* is the effluent turbidity normalized by the raw water turbidity) improves linearly with floc blanket depth (Figure 16). Our initial studies indicate that floc blankets can reduce effluent turbidity by a factor of 10 with a residence time of only 15 minutes, and thus they can serve as an important unit process in a high-rate treatment train.

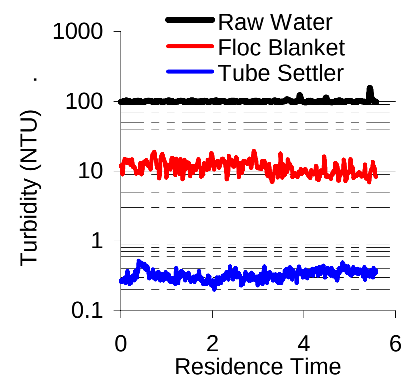

Figure 17. Continuously sampled turbidity readings for raw water influent, and floc blanket and tube settler effluent as a function of hydraulic residence time in the sedimentation tank

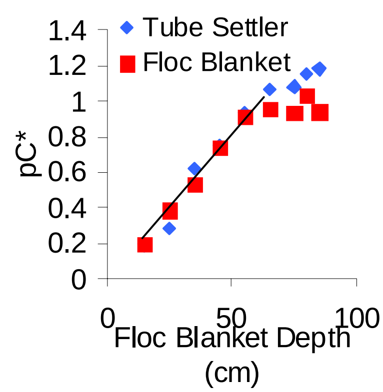

Figure 16. Effect of floc blanket thickness on particle removal efficiency in the effluent from a floc blanket and subsequent plate settler.

We will continue to characterize the performance of floc blankets and to develop a performance model that takes into account the flocculated suspension size distribution as well as floc blanket characteristics. Floc blanket failure modes will also be evaluated to determine operational challenges.

Sedimentation

Flocculator and sedimentation tank designs are coupled in two significant ways. First, the most economical tank design (an important characteristic in poor communities) will likely have the sedimentation and flocculation tanks sharing a common level foundation. Thus the water depth at the effluent of the flocculation tank will be the same as the water depth in the sedimentation tanks. The water depth at the influent of the flocculation tank will be slightly higher due to head loss through the flocculation tank. Second, a desired performance level of the coupled processes can be attained either by making an excellent flocculator that produces only rapidly settling flocs or by making an excellent sedimentation tank that can capture slow settling particles produced by a suboptimal flocculator. The optimal solution would be to create reactor designs for both flocculator and sedimentation tanks that minimize construction and operation costs while achieving the target particle capture efficiency. It is this coupled optimum that we intend to characterize.

There are three major choices for sedimentation tank design.

1. Horizontal (or radial) flow vs. vertical flow
2. Presence or absence of plate settlers
3. Presence or absence of a floc blanket

Each of these design choices includes a significant number of additional design parameters for the specific geometry, fluid velocities, and inlet and outlet conditions.

It is noteworthy that state of the art sedimentation tank designs emphasize horizontal or radial flow tanks with the option of adding plate or tube settlers. Horizontal flow sedimentation tanks are plagued with non-uniform flow, convection currents, and the need to maintain very low horizontal velocities to prevent floc resuspension. The lack of adequate flow control in horizontal flow sedimentation tanks makes it difficult to achieve uniform velocity through the plate settlers. Hydraulic analysis of a horizontal flow sedimentation tank with plate settlers reveals that the velocity through the plates furthest from the inlet will be highest as a result of conversion of the kinetic energy contained in the horizontal flow velocity into potential energy.

Horizontal flow sedimentation tanks are not optimally coupled with plate settlers and are incompatible with floc blankets. In addition, horizontal flow tanks require depths in excess of 2.4 m (Letterman, 1999). The standard designs of horizontal flow tanks have lengths that are 20 times their depth and depths that are similar to the width. This design results in horizontal velocities that are 20 times the equivalent upflow velocity. Given that turbulent eddies have velocities that are on the order of 10% of the mean flow velocity, horizontal flow sedimentation tanks have higher vertical velocities than would be achieved by similarly sized vertical flow sedimentation tanks. The jet action and increased turbulence from the inlets makes the transport of flocs to the bottom of the horizontal flow sedimentation tank even more difficult. For these reasons we have concluded that horizontal flow sedimentation tanks cannot be designed to perform as well as vertical flow sedimentation tanks.

In the spring of 2006, the AguaClara team designed a high-rate vertical flow sedimentation tank with plate settlers and a water depth of 2 m that was then built in Ojojona, Honduras (Figure 3). This plant is able to meet the Honduran water standard of 5 NTU even though the raw water has a high organic content. Two more AguaClara water treatment plants with a total capacity of 2750 L/min came on line during the summer of 2008. Analysis of the sedimentation tank design and continued encouragement from APP to reduce construction costs led us to redesign our method of distributing the water into the bottom of the sedimentation tank. The new design was finalized in November of 2008 and a small plant that will serve 2000 people will be coming on line in Honduras in early March of 2009. The new design fully utilizes the bottom of the sedimentation tank with entrance manifolds placed in what had previously been lost space.

Plate settlers have significant advantages, because they reduce the size needed for sedimentation tanks and thus decrease construction costs. It is very clear that plate settlers improve sedimentation tank performance. It is not clear if the “standard” spacing of approximately 5 cm between plates is the optimal design. We have also shown that plate settlers substantially improve particle capture above floc blankets (Figure 17). Fortuitously, the required up flow velocity for floc blankets (approximately 100 m/day) is well matched to the performance of plate settlers. The performance gain of plate settlers is given by

$$\frac{V_{up}}{V_c} = 1 + \frac{L}{b}\cos\alpha\sin\alpha \qquad (8)$$

where V_{up} is the up flow velocity below the plate settlers, V_c is the capture velocity in the plate settlers, L, b, and α are the length, spacing and angle of the plate settlers respectively. A capture velocity of 10 m/day is our current design standard. A ratio of V_{up}/V_c of 10 is easily obtained and leads to the question of the optimal plate settler spacing. The advantage of a smaller spacing is that the plate settler length, and hence sedimentation tank depth, can be reduced. We will determine the failure modes and the optimal spacing for plate settlers using the apparatus shown in Figure 10.

International Partners

We have been collaborating with Agua Para el Pueblo (APP), a Honduran NGO, since 2004. We have two Cornell graduates on year long internship assignments with APP to facilitate capacity building and to provide feedback to the team at Cornell on facility performance and potential areas for improving the designs. The feedback from the field, coupled with our ability to move quickly through the design, construction, and testing phase with full scale municipal water treatment plants, enables us to rapidly test and improve our design algorithms.

The AguaClara team has a solid working relationship with APP. They have built three of the AguaClara water treatment plants in Honduras and are encouraging us to develop even more economical designs. The goal is to get costs low enough so that communities can self-finance the AguaClara plants. APP is currently negotiating with two municipalities with populations over 10,000 each that are interested in acquiring AguaClara plants. There are many thousands of communities throughout Latin America that have untreated surface water, and thus there is an excellent opportunity to continue building AguaClara facilities with improved designs. Since it only takes about 6 months to build a drinking water treatment plant, improved theoretical understandings can propagate into full-scale water treatment plants in approximately 1 year. We also anticipate flocculator design changes and have constructed the facilities so the energy dissipation rate can be adjusted relatively easily in the flocculators.

We anticipate establishing new partnerships with organizations in other regions that also have inadequately treated surface waters used as drinking water. We are currently developing a partnership with the Chemical Engineering School of the University of Guayaquil, Ecuador. They would like to build a pilot scale AguaClara facility to test its performance for application in Ecuador.

Knowledge Dissemination and Broader Impacts

Experimental results and the flocculator and sedimentation design guidelines will be posted on the AguaClara wiki (aguaclara.cee.cornell.edu). The wiki has open access in order to facilitate knowledge transfer to the global water supply community as they work to provide cost-effective water treatment to protect the health of the approximately 2 billion people who do not yet have access to safe drinking water. Our online design tool also will be available globally for engineers to rapidly create AguaClara water treatment plant designs.

The web-based automated design tool will deliver fully-detailed, three-dimensional drawings and parts lists for AguaClara water treatment plants (Figure 4). The design tool incorporates algorithms for all aspects of the plant, including pipe sizing, hydraulic-flocculator baffle spacing, gravity-powered chemical feed system, hydraulic manifold designs for sedimentation tank inlet and outlet, channel and port designs to prevent floc breakup, and plate settler design. An engineer will select flow capacity, wall thickness, and a small number of other parameters. A customized design is then created in approximately 2 minutes of computation time and emailed to the engineer. All dimensions are calculated using algorithms implemented in MathCAD. We will continue to upgrade the scaling algorithms that are used to design these plants, and will integrate the findings from this research project. This web-based tool will significantly reduce engineering design costs for water treatment facilities.

The proposed research is an integral part of the AguaClara team project that is growing every year and that currently involves approximately 40 undergraduate and graduate students. The hands-on research and design experience with an international context creates an engineering education that changes lives. Students learn the value of questioning and evaluating design assumptions. They learn how to identify design guidelines that don’t scale correctly. They learn to identify critical constraints and to express those constraints in dimensionless form so they can be scaled. They routinely develop new algorithms to optimize the design of various components of the water treatment plants. In addition, students learn the dangers of group think. As we explore new, more economical, surface water treatment plant designs, we take the time to seek out dissenting views. We create a careful balance between testing the limits of our knowledge and exercising our ethical responsibility to design facilities that perform well and protect public health.

Approximately 20 AguaClara team members per year participate in a two-week cultural and engineering immersion field experience. One focus of the educational trip is to illustrate the cost to society represented by the poorly engineered “high tech” and highly-dependent infrastructure that has too often been the only option available to poor communities. Another goal is to encourage students to value the knowledge and experience of our partners who do the structural engineering and of community members who construct and operate the AguaClara water treatment plants. All students come away with a renewed appreciation for the value of robust engineering designs that make an ongoing difference, especially in the health of children.

Prior award

The PIs received NSF funding (award number 0604566) of $240,000 effective 08/15/2006 to 07/31/2009 for Enhanced Microbe Removal in Granular Media using an Attachment Mediating Polymer. The research objectives are to improve surface water treatment technologies in order to make them sustainable and accessible in the context of underdeveloped countries. The research was motivated by the fact that slow sand filters pretreated with acid soluble material extracted from Cayuga Lake particulate matter were capable of achieving greater than 99.9999% removal of *E. coli*. Our research subsequently established that naturally occurring aluminum contained in the acid extract was the active filter ripening agent (Weber-Shirk and Chan, 2007) and it became clear that the performance of municipal rapid sand filters could also be enhanced by appropriate pretreatment of the filter media. Automated process control technology developed by PI Weber-Shirk (2008) permitted pre-programming a set of experimental conditions that are monitored by online pressure and turbidity sensors. Computerized experimental automation allowed rapid evaluation of alternative methods for pretreating filter media. Methods have now been developed for enhancing municipal-scale rapid sand filter performance by *in situ* pretreatment of the filter medium.

96% removal of test particles (kaolin clay) was attained after pretreatment of a sand medium using down-flow application of aluminum hydroxide and iron hydroxide suspensions. This level of particle removal was accomplished without any coagulation or flocculation of the raw water. This high particle capture was achieved in a 7.5 cm deep column containing 0.8 to 1.0 mm sand and operated at 5 m/hr. It is well known that rapid sand filters are able to remove particles that have been treated with coagulants much more efficiently than they can remove untreated particles, and thus we expect that the particle capture efficiency for destabilized particles will be even higher than the values that we are obtaining for untreated particles.

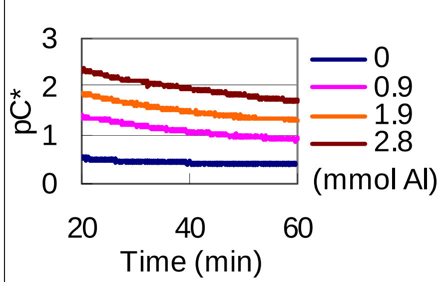

Figure 18. Filter performance enhancement by alum filter aid. The influent turbidity was ~60 NTU.

Downflow application of filter aids focused deposition at the top of the sand medium and increased head loss. Thus, we worked to develop pretreatment methods that would attain a more uniform application of the ripening agent throughout the filter bed. Sand medium pretreated with the ripening agent during the end of the backwash cycle achieved 99% particle removal with only nominal additional head loss caused by the pretreatment (Figure 18). Conventional rapid sand filtration plants are operated with an influent turbidity that is typically < 5 NTU over a cycle of two to three days. When low turbidity (~5 NTU with 0.5 mg/L HA) synthetic raw water was filtered by a pretreated filter for 2 days, turbidity removal was improved for the first 20 hours of operation compared to conventional direct filtration (Figure 19). The filtered effluent turbidity was below detection limit (0.01 NTU) for the first 6 hours of operation.

We are preparing to test this new technology full scale at the Cornell Water Filtration Plant. We also plan to test the filter performance following flocculation and sedimentation to assess performance as a function of time given these more realistic particle conditions. If *in situ* filter media pretreatment proves to be a viable technology for providing improved protection against chlorine resistant pathogens, then filter design should be reevaluated to optimize filter performance using this new technology.

The research has resulted in a web-based description of the process control software, 3 published peer-review papers, and 3 conference presentations. One additional paper is in review and 3 are in preparation. The research supported fully or in part the training of one Ph.D and 3 M.S students. One former undergraduate participant won a Fulbright award and will begin working full-time in Honduras in March 2009 to document the performance of full-scale treatment plants.

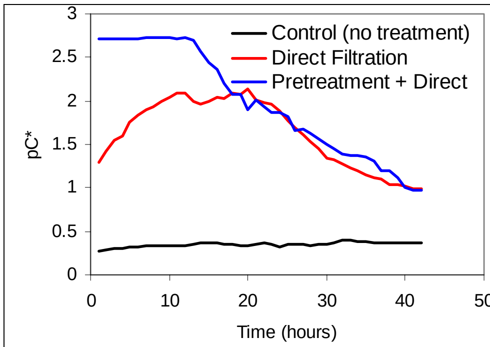

Figure 19. Filter performance showing the added improvement of pretreatment. The raw water had a turbidity of 5 NTU and had 0.5 mg/L humic acid (HA).

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