APPENDIX G

Enhanced Chlorination / De-Chlorination Evaluation

Appendix G

Enhanced Chlorination / De-Chlorination

Workshop #1 – March 15, 2007

Enhanced Chlorination/De-Chlorination Evaluation
Scoping Session Workshop
Meeting Notes

1. The Enhanced Chlorination/De-Chlorination Evaluation Scoping Session Workshop with regard to the disinfection of the effluent wastewater for Pima County Regional Optimization Master Plan was held on March 15, 2007. The agenda is attached. The following were in attendance:

PCWMD
Director
Michael Gritzuk
Deputy Directors
Paul Bennett
Mike Bunch
Jackson Jenkins
PCWMD Staff
Gary Blomstrom
Jim Doyle
Laura Fairbanks
Dave Garrett
Byron McMillan
Jeff Prevatt
Ron Riska, Project Manager
Mandley Rust
John Sherlock
Legal
Harlan Agnew
Barbara McMurray
Chuck Wesselhoff

TUCSON WATER
Tucson Water Staff
Melodee Loyer
Dennis Rule
Tim Thomure

GREELEY AND HANSEN PROJECT TEAM
Jerry Bish
Andy Richardson
Art Umble

ADDITIONAL ATTENDEES
Larry Leong, Kennedy/Jenks
Sam Jeyanayagam, MPI
David Murray, Brown and Caldwell
Jennifer McPhillips, MPI

2. Major topics of the workshop were:

- Current disinfection conditions/performance
- BADCT standards
- Other effluent requirements
- Investigation / study success factors
- Investigation / study objectives
- Investigation / study tasks

A set of handouts were provided to each attendee at the workshop. Throughout the workshop a set of notes were recorded on "flip-charts." Those notes summarize questions, comments and notes to be

utilized by the project team while conducting the study. The flip chart notes are included at the end of the meeting notes.

3. Mike Gritzuk welcomed the attendees to the workshop and articulated the focus of the meeting. He stated that the study needed to focus on three objectives:

   - Meet a Class A+ effluent quality discharge
   - Meet the BADCT standards
   - Minimize the need or necessity of spending nearly $70 million (which would be the case if the ultimate process selected for disinfection is filtration coupled with UV)

4. After introductions of the process experts: Larry Leong, Dave Murray, Sam Jeyanayagam and Art Umble, a brief discussion of various disinfection issues ensued. Jackson Jenkins mentioned that perhaps filtration would be required along with chlorination instead of ultraviolet (UV) disinfection to meet the future standards. Mike Gritzuk indicated that if filtration is necessary perhaps it is a different type at a lower cost to the County. Harlan Agnew cautioned that all effluent parameters will need to be met. Key issues from the regulatory perspective include the Aquifer Protection Permit (which has implications for disinfection by-products); BADCT standards for effluent quality (which define the bacteria limits in the discharge in terms of 4 of 7 samples taken within a week period must register as "non-detect", with no single (fecal) sample exceeding 23 MPN; the disinfection standards as defined by the AZPDES permit limit chlorine residual in the effluent to less than 11 µg/L for a daily maximum and less than 8 µg/L on a monthly average. Also, the Whole Effluent Toxicity (WET) requirements will need to be addressed.

   Dennis Rule asked if A+ effluent was a driver for the study. This was articulated as a goal to meet the requirements for reclaimed water in the spirit of cooperation with Tucson Water and the overall needs of the community for water. Harlan Agnew indicated that ADEQ, as a policy, wants the whole effluent to be treated to an optimal quality. For example, the state would not want a facility to provide Class A+ to Tucson Water and Class B+ to the river.

5. Andy Richardson outlined the meeting topics and objectives. He further elaborated on his role as facilitator and encouraged all to participate. The workshop objectives were to develop the scope for the enhanced chlorination/de-chlorination investigation and study, and to identify issues and concerns regarding the investigation/study.

   Overview, agenda, meeting objectives, and ground rules were covered on pages 1 through 5 of the handout.

6. Jerry Bish provided overview of the cost differential between UV (with filtration) and enhanced chlorination/de-chlorination (without filtration) disinfection systems and a summary of the disinfection systems in service at Ina Road WPCF and Roger Road WWTP.

The potential capital costs savings for the County is over $70 million for a reliable, effective chlorine based disinfection system. The disinfection process utilized at the Ina and Roger plants is conventional sodium hypochlorite disinfection technology followed by sodium bi-sulfite de-chlorination. A 12.5 % solution of sodium hypochlorite and a 40 % solution of sodium bi-sulfite are delivered on site for use. There are three sets of contact tanks at the two plants, which are designed to provide a detention time of 30 minutes at average design flows. One set of contact tanks at the Ina Road WPCF serves the new biological nutrient removal activated sludge process (BNRAS) facility and another set serves the high purity oxygen activated sludge process (HPO).

Performance data at the two treatment plants for the past six months was plotted and presented. The data trend is a steady improvement in lowering chlorine dosages and in reducing fecal and E. coli counts in the effluent grab samples. This is in response to initiatives undertaken by Operations to improve the disinfection system performance. Sam Jeyanayagam pointed out that there is a different maximum allowable standard under BADCT for fecal (23 cfu) and E. coli (15 cfu). Also, it was suggested that Pima County meet with ADEQ. Mike Gritzuk stated that Pima County had indicated that they would meet ADEQ on this topic and a meeting was to be scheduled soon.

Lastly, the wastewater treatment system process to be in place when the BADCT rules take effect was summarized. A Bardenpho system operating with an effluent TKN less than 6.5 mg/l will be constructed and in operation at the time that Pima County is required to meet the BADCT requirements.

Project cost drivers, current operating features and status of the disinfection process at Roger Road WWTP and Ina Road WPCF were covered on pages 5 through 17 of the handout.

7. Art Umble presented the scope of the enhanced chlorination investigation and study. The success factors and workplan flowsheet were presented to demonstrate how the project elements are integrated to achieve project results within a limited timeframe. The investigation and study is a three-pronged approach that can proceed in parallel paths – 1) literature research, 2) insitu study, and 3) laboratory bench scale study. Chlorination disinfection has been well studied and researched over the last 100 years. The key for this project is to extract pertinent scientific data from the available literature to support the efficacy of enhanced chlorination. The insitu study will be used in conjunction with the bench scale study to determine the capabilities of the existing chlorine disinfection system configuration to determine the gap, if any, in meeting BADCT requirements with the conventional disinfection approach and what system improvements can be made for enhanced performance. Another key of the investigation is to demonstrate that chlorination technology is working elsewhere in meeting strict pathogen removal standards.

   There was a discussion about which disinfection system would be used for insitu evaluation. While the BNRAS most closely represents the future process for removal of total nitrogen from the wastewater, it is being operated abnormally at steady-state mode until some hydraulic control elements are made functional at the plant. This may limit its use for insitu field evaluations in the early study phases. Larry Leong asked if the standard was for fecal or E. coli or both. The response was that the regulations permit either. In this case, it was suggested that the County adopt an E. coli

standard for reporting to the regulators. It was further explained that the standard was for a calendar seven days (week basis) and not a running 7-day average.

Byron McMillan asked if UV will meet the disinfection standards. It was suggested that in California and Florida, where strict pathogen removal standards are in place, that facilities with UV are struggling for compliance. Mike Gritzuk stated that ADEQ BADCT requirements specifically lists UV, chlorination, ozone and soil aquifer treatment (SAT) as disinfection technologies. Jennifer McPhillips offered that ADEQ prefers filters to be included on effluent discharges. Filters could reduce chlorine and de-chlorination chemical consumption.

Ron Riska indicted that the disinfection study needs to identify the best present worth approach. Art Umble indicated that that could be a mixed oxidant process and this will be explored in the study. Melodee Loyer cautioned that the use of mixed oxidants could create other issues and consequences that will need to be recognized and addressed.

Jeff Prevatt indicated that there is a strong possibility of fecal re-growth in the outfall conduit before sampling. The County is working with the regulators on relocating the point of compliance for the fecal sampling upstream in the system, while keeping the chlorine residual monitoring located downstream. Larry Leong suggested that the laboratory may want to consider a modification of the test procedures to include multiple dilutions to increase sensitivity.

For insitu testing on the contact tanks, a basic tracer test is proposed with dye or fluoride based tracers. Jeff Prevatt has access to fluorometer test instrumentation as required for the testing.

Byron McMillan reemphasized that the County needs to meet the chlorine residuals requirements, WET limits, as well as, BADCT requirements.

Larry Leong has a large database of disinfection information from a WERF study. This can be used to some extent to screen potential plant sites for further investigations relative to the Pima County disinfection issues.

The elements and schedule for the enhanced chlorination investigation and study were covered on pages 17 through 24 of the handout.

8. Ron Riska asked the process experts what other items need to be included in the study outline.

   Dave Murray stated that the proposed scope outline seemed appropriate, but asked how will the in-plant studies, which will be mostly dry weather, reflect all weather conditions? It will be difficult to demonstrate system performance under severe conditions, such as a severe wet weather event, when the testing is designed primarily around dry weather conditions. In addition, it was offered that testing of the system performance should be conducted on both filtered and non-filtered samples. This is to reflect the impact of solids in the effluent on disinfection testing.

Larry Leong offered that obtaining data from comparable plant operations may prove difficult simply due to the fact that some operators/managers will be reluctant to share information. They may view this study as subjecting their data unnecessarily to public or regulatory scrutiny. Further, it was suggested that the proposed 90-day schedule is too tight. It will not be possible in this period of time to conduct the full literature search and to conduct a search of available data from comparable facilities. In addition, the proposed schedule is too tight to allow for adequate statistical analysis to be done on testing the plant at full scale. The bench scale studies should be extended as well. The concern is that in order to gain enough data to conduct appropriate and defendable statistical analysis, at least one to one and one-half years of data is required. At least 30 tests are needed for each operation mode in order to establish a credible data set. At this point it was stated that at 90 days a "go/no-go" decision would be made to continue the enhanced chlorination or discontinue the study based on the evidence developed at that time.

Across the US, approximately 17% of the municipal wastewater treatment plants are using UV for disinfection. Nearly 75% are using some form of chlorine-based disinfection. The remaining plants are using some other means of oxidation method for disinfection. This raised the question provided earlier as to whether this study should include evaluating the applicability of UV for the Ina Road and Roger Road facilities. The general indication was that the study should include enough information on UV disinfection for comparative purposes.

Sam Jeyanayagam offered that in compiling data from comparable plants, it will be important to establish "lessons learned" from those that have had problems with similar systems. Too often that data is unavailable. Data is often used from plants that have been successful, and data from those that have not been successful is either not available, or is overlooked. It will be important in this study to identify where problem areas have occurred and to understand the reasons behind those problems and how they were resolved.

Further there needs to be caution with regard to "predicting" the performance of these systems in the long term. No one knows what the future will hold in terms of community growth (effecting the characteristics of the influent wastewater), the long term plant performance, the regulatory environment, and so forth. Caution must therefore be taken so as to not "over-predict" the guarantees of the system's performance.

John Sherlock offered that both Ina Road and Roger Road plants need to be examined because each facility has significantly different influent characteristics. In the past, the facilities have experienced "nitrite lock", primarily during periods in the summer months. This issue is important and needs to be considered when the study is conducted.

The investigation team should consider the possibility of reducing the bacteria in an upstream process to reduce the demand on the chlorination/de-chlorination system. For example, would adding chemicals upstream in an aeration basin or a final clarifier to further reduce solids (and the associated bacteria) help reduce the chlorine demand?

A review should be done of the control loop systems for the de-chlorination process. One plant uses a concentration-based control, while the other uses the ORP control. Data indicates that historically, the concentration-based control methodology has performed better.

For the WET testing, ammonia has been the chemical of concern, but the use of excess bi-sulfite may also be of concern. This issue needs to be considered in the project.

Melodee Loyer offered that when looking at the option of mixed oxidants, there must be consideration given to "unintended consequences" that may result. This specifically relates to any safety and public health issues associated with the presence of these oxidants. As much as is possible, these potential concerns must be identified and addressed at the outset. The concern is that there is not enough time proposed in the study schedule to allow for this research. Also, if the Roger Road facility is used for the field testing, Tucson Water would be willing to participate, specifically for issues related to filtered versus unfiltered samples since Tucson Water filters the effluent at their Sweetwater facility adjacent to that plant.

Paul Bennett stated that there may not be much benefit garnered from doing testing at the Roger Road facility simply because as part of the facility master plan, the existing facility will be demolished and a new facility built in its place. Thus, testing the existing facilities may not generate useful data. Furthermore, recommendations need to be "operator friendly." This means that specific communications protocol need to be set up and followed throughout the study that incorporates input from operations staff.

Jeff Prevatt (Laboratory Director) offered that the analytical laboratory staff would cooperate fully with the needs of the study in terms of laboratory facility, equipment availability and staff participation as time and schedules permit.

Ron Riska commented that the County originally suggested that the scope time table should be in the 60 to 90-day frame. This may not be enough time to complete the necessary and critical elements of the study. Therefore, it seems reasonable that the study be lengthened by at least two additional months. The challenge here is that this study represents the "last piece of critical information" needed to complete the Regional Optimization Master Plan (ROMP). Delaying the results of this study too long could jeopardize the implementation schedules for the ROMP.

Agenda
Enhanced Chlorination/De-Chlorination Evaluation Scoping Session
March 15, 2007

Time	Topic	Presenter
8:45 am	*Outlying Facilities Offices –4527 W. Walker Road (near intersection of Ina Road and I-10)*	
9:00 am	Opening Session	
	• Welcoming Remarks / History and Objective	Mike Gritzuk
	• Review Agenda	Andy Richardson
9:15 am	Overview of Pima County Facilities	Jerry Bish
	• Existing Conditions: Chlorination Disinfection System	
	• Existing Conditions: Chlorination Disinfection System Performance	
	• Overview of Current BADCT Standards	
	• Overview Description of Wastewater Process when BADCT Takes Effect	
9:45 am	Develop Set of Critical Success Factors	Art Umble
9:55 am	Define Literature Review Objectives	Art Umble
10:05 am	Chlorine-Based Disinfection Alternative Evaluation	Art Umble
11:15 am	Alternative Chlorine-Based Disinfection Evaluations	Art Umble
11:35 am	Future Investigation/Study Objectives	Art Umble
11:45 am	Summary Wrap-Up	Andy Richardson
	• Comments by Group	
	• Closing Remarks	Mike Gritzuk
12:00 pm	Adjourn	

Flip Chart Notes – March 15, 2007

OBJECTIVES

- Save $70 million
- Meet permit requirements
- CL_2 residual water quality standard
- Whole effluent toxicity standards
- THM's in APP
- "Parking Lot" crypto and giardia - MCL
- Per ADEQ have to treat "total" flow to same quality.
- "Bullet Proof vs. some risk
- Cost benefit vs. risk

DATA NEEDED

- Get volumes in each CL_2 tank
- CL_2 @ 8PPM to 11PPM avg.
- Need to meet BADCT coliform or e-coli limit
- Need to look at steady-state vs. diurnal flow

SCOPE

- Benchmarking – who else is doing enhanced CL_2 /De- CL_2
- Need to make sure that the insitu condition is a good representation of future facilities.
- May need to bring in a "pilot plant"
- Need to make sure we use quality of effluent that is representation of what future effluent will be.
- Use e-coli as standard in permit
- What is the standard? Is it 7 days for a calendar week or 7 day moving median
- Scope and work effluent will be discussed with ADEQ at start of investigation
- System specification is a final deliverable of this investigation
- Permit - change sample location for cfu analysis
- Need to have team determined method for analysis
- Consider system with water champ for pilot scale?
- How are we going to make sure effluent quality matches future effluent?
- How to address wet weather conditions?
- Present or absence of solids relate to use of filters
- What happens if we have to filter?
- Review operating data at other locations
- Concern: will information be shared when a plant is in trouble?
- Concern on amount of data accessibility in short period
- How to use existing facilities to match future conditions
- 30 trials for a given condition for testing insitu
- May want to have study go longer
- Look at extending time to make certain
- How far can we go at first
- Find out "lessons Learned" – may not be able to get information

- Future process is an issue – need to pay attention to this
- May not have facility that will match future
- More time at Ina Rd. and less time at Roger. Look at influent characteristics to make sure using right data
- Look at work that has been on reported on fecal loadings upstream of CL_2 addition
- Control systems now vs. future
- Maybe a phased implementation - get results and then do some additional work
- Whatever we come up with – make sure we are aware of impact
- 3 to 4 month period for "go-no/go"
- Add some information on "UV" as a comparison in the benefit/cost analysis – use literature review data
- Need to be aware of how plants operates when interconnected
- Why testing at Roger may not be necessary
- On De-CL_2 what process mimics residual CL_2
- Visit w/Jeff Prevatt before doing insitu work
- Only look CA, FL, AZ for last 5 years

Pima County Wastewater Regional Optimization Plan Study

Enhanced Chlorination / Dechlorination Evaluation Scoping Session

March 15, 2007

Workshop Presenters

- Mike Gritzuk — Welcome / Closing
- Andy Richardson — Facilitator
- Jerry Bish — Overview of Facilities
- Art Umble — Project Scope

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Welcoming Remarks

Mike Gritzuk

Overview

Andy Richardson

Agenda

- History and objectives
- Current conditions / performances
- Current BADCT standards
- When BADCT takes effect
- Critical success factors
- Literature review objectives
- Chlorine-based disinfection
- Alternative chlorine-based disinfection
- Investigation / study objectives

5

Groundrules

- Success is the responsibility of all
- Everyone shares the responsibility for success
- Everyone must participate fully to the extend of their expertise
- We agree to speak up honestly and with candor

6

Groundrules *(continued)*

- Disagreements are with opinions or issues, and have basis in fact, not with personalities
- Listen attentively and respectfully to others
- Participate conscientiously
- Understanding is our objective, but consensus is not required
- Adhere to these groundrules and hold each other accountable

7

Role of Facilitator

- Remain neutral and objective
- Expedite adherence to agenda and schedule
- Ensure an equal opportunity to be heard
- Keep group focused on discussion as planned, place items in "parking lot"

8

Role of Facilitator

- Remind all of groundrules
- Negotiate changes in agenda, schedule, or procedure
- Manage discussion, sequence speakers, and exercise leadership

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Pima County Wastewater Management Department

GREELEY AND HANSEN

Overview of Pima County Facilities

Jerry Bish

UV Disinfection vs. Enhanced Chlorination – Systems

- UV Requirements
  - Lift pump station
  - Filtration
  - High Intensity UV
- Enhanced Chlorination
  - Contact Tank (longer retention)
  - Higher sodium hypochlorite dosages
  - Higher sodium bisulfite dosages

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UV Disinfection vs. Enhanced Chlorination – Cost Impacts

- UV Costs $91.0 million
  - Construction/Contingency/ Engineering
- Enhanced Chlorination $17.6 million
  - Construction/Contingency/ Engineering

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Existing Treatment Processes

- Ina Road WPCF
  - High purity oxygen
    - Effluent 30/30
  - BNRAS
    - Effluent TKN < 15 mg/L
- Roger Road WWTP
  - BT/AS
    - Effluent 30/30

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Existing Chlorine Systems

- Sodium hypochlorite (12.5% solution)
- Contact tanks (3 sets)
  (30 minutes at average Q)
- Sodium bisulfite (dechlorination)
- Chemicals flow paced

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Ina Road WPCF Site

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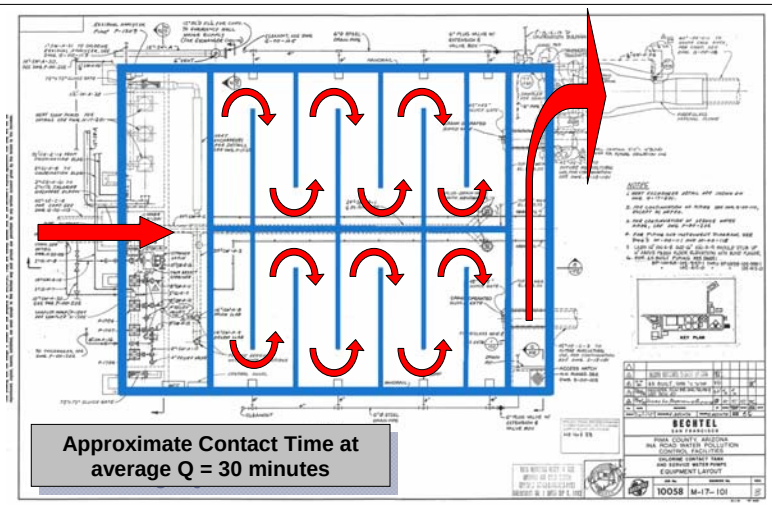
Ina Road Chlorination Facilities – HPO



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Ina Road HPO Chlorination Photo

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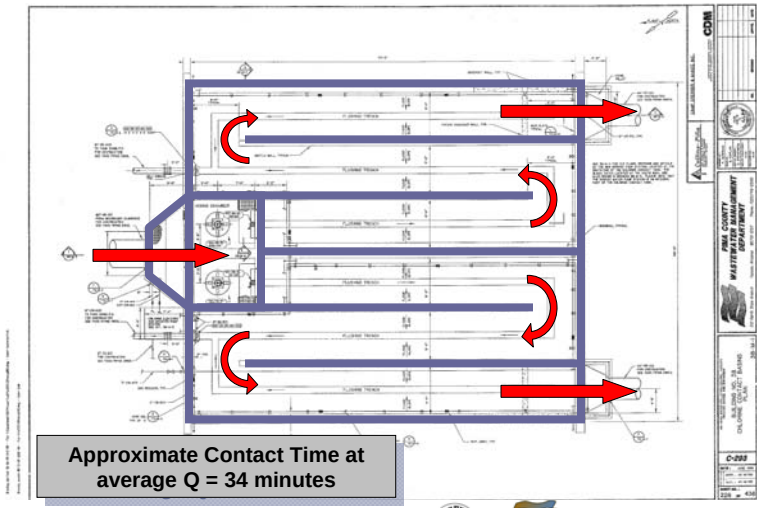
Ina Road Chlorination Facilities – BNRAS Plan



Approximate Contact Time at average Q = 34 minutes

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Ina Road BNRAS Chlorination Contact Tank

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Roger Road WWTP Site

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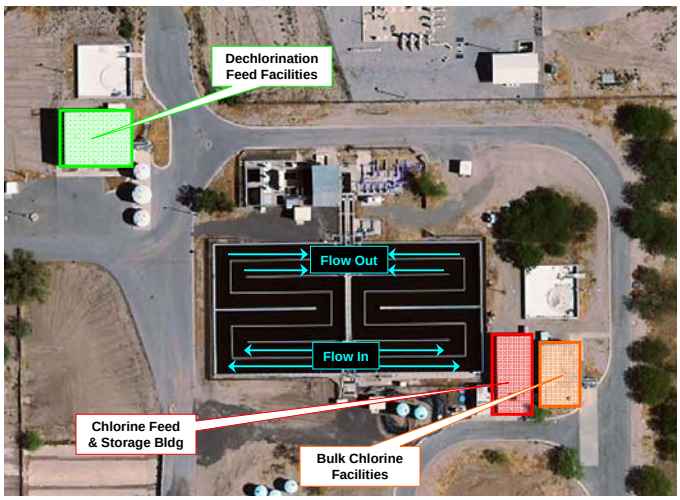
Roger Road Chlorination Facilities – Plan



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Roger Road – Chlorination Equipment

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Roger Road – Chlorination Contact Tank

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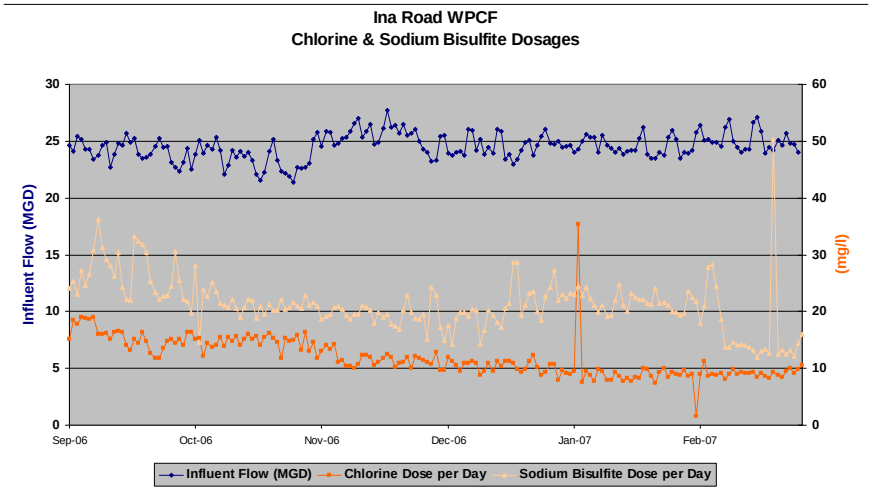
Ina Road Performance



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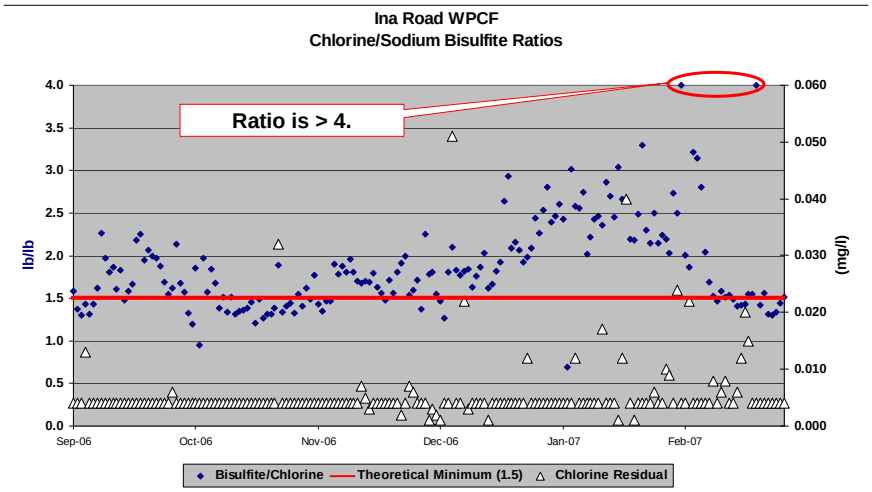
Ina Road Performance



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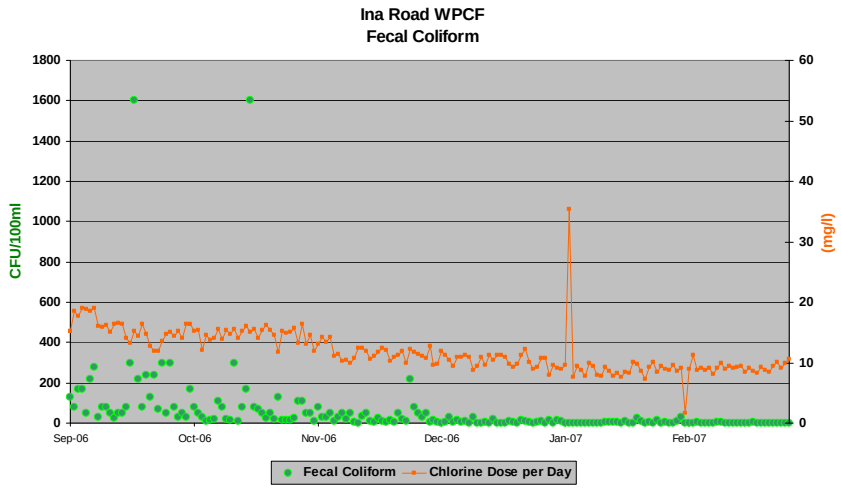
Ina Road Performance



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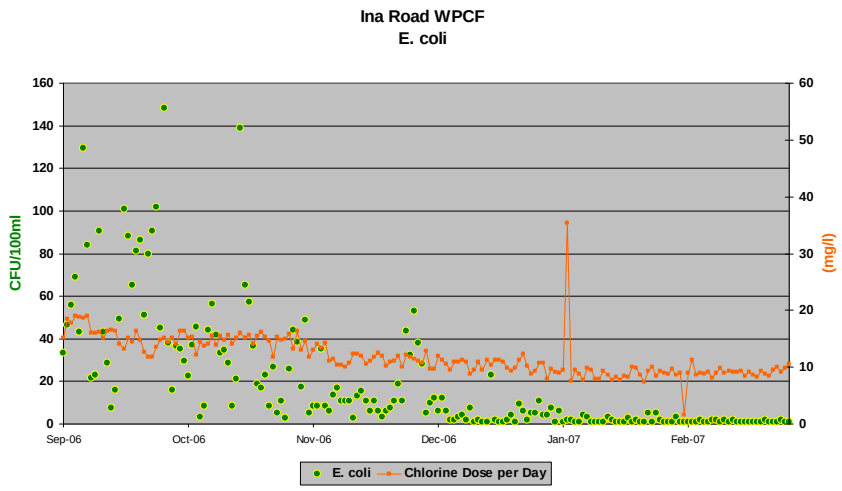
Ina Road Performance



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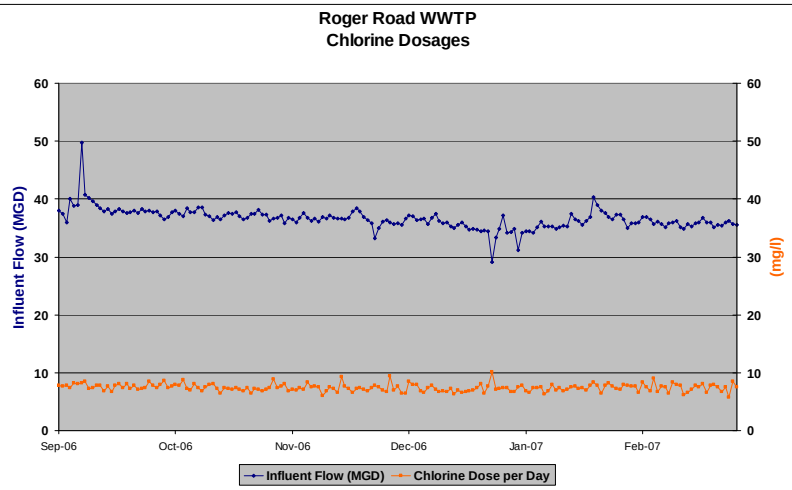
Roger Road Performance



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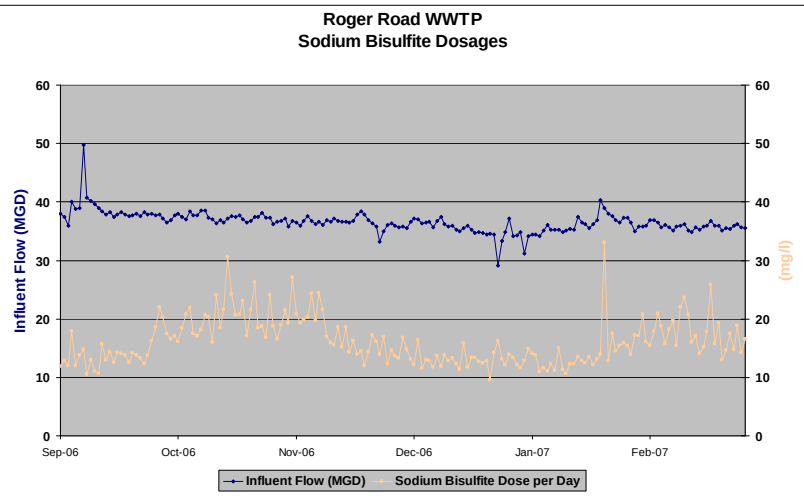
Roger Road Performance



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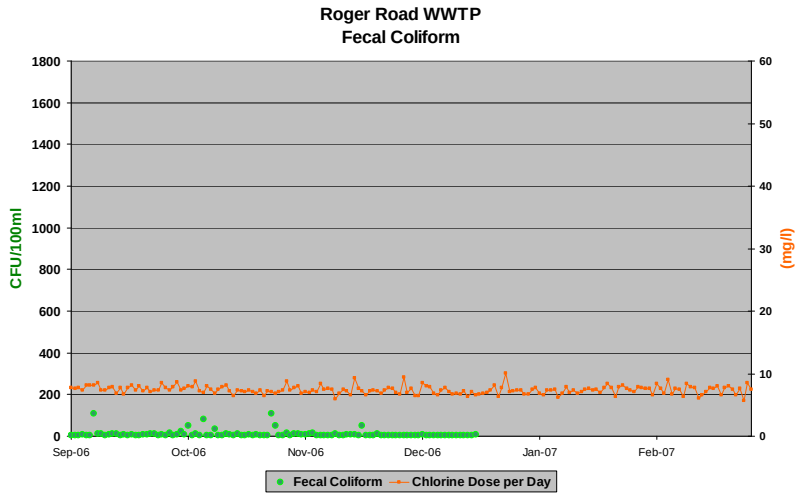
Roger Road Performance



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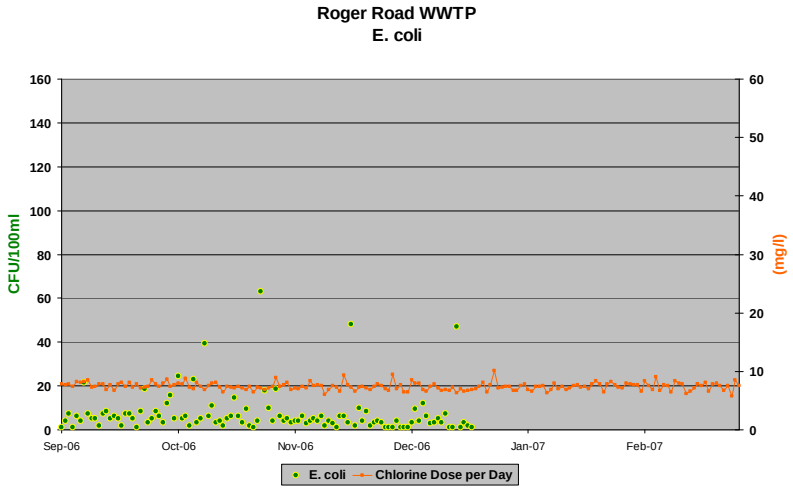
Roger Road Performance



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BADCT Requirements

- Disinfection
  - No detect (E. coli) in 4 out of 7 samples per week
  - None to exceed 23/100 mL

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Process When BADCT Takes Effect

- Treatment process – Bardenpho
- Effluent TKN ≥ 6.5 mg/L
- Future:
  - Effluent P > 1.0 mg/L

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Pima County Wastewater Management Department

GREELEY AND HANSEN

Enhanced Chlorination Project Scope

Art Umble

Critical Success Factors

- Meets BADCT requirements
- Performs without filtration
- Demonstrates performance elsewhere
- Demonstrates performance at Roger Road and Ina Road

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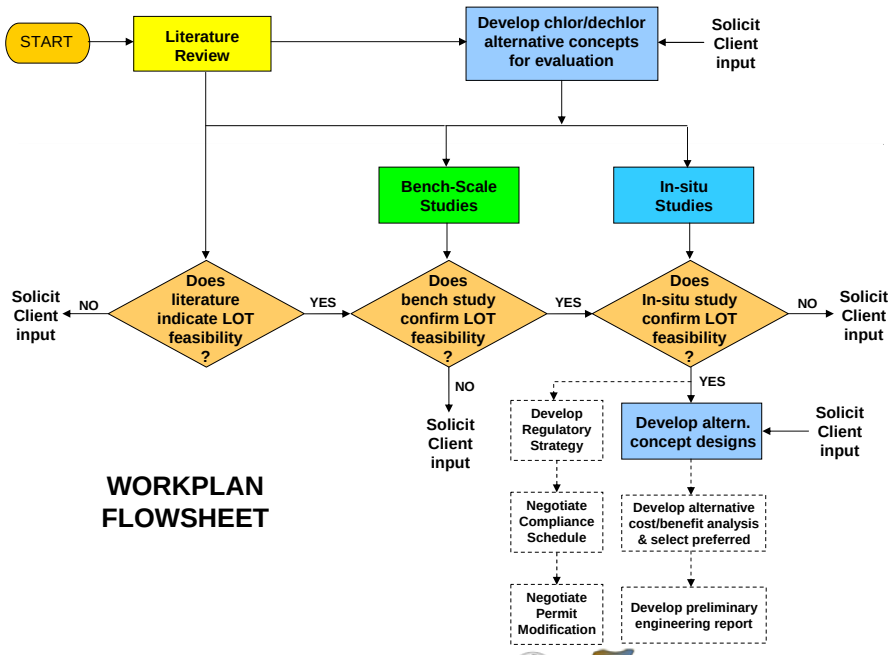

WORKPLAN FLOWSHEET

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Basic / Fundamental Research Actions

- Laboratory study
  - Chlor/dechlor fundamental reaction chemistry and reaction kinetics research has been completed
- Literature search
  - Technical justification for applying existing technology for environmental protection and public health
  - Review the realm of feasible alternatives to conventional chlor/dechlor practices
  - Review the LOT for inactivation and environmental protection
  - Review the relationship between LOT and current BADCT and permit limits
  - Review the LOT performance equivalency with other BADCT technologies
  - Review the statistical limitations of the technology

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Literature Review and Research Results

- Focus of Review: Disinfection for Water Reuse Applications*
- Identify chlor/dechlor disinfection facility enhancement research studies
- Identify facility enhancements with respect to regulatory compliance
- Applicability of models (Collins, Collins-Selleck, etc.) to existing disinfection efficacy
- Identify comparable facilities that utilize enhanced chlor/dechlor disinfection systems
- Establish accepted capital and O&M cost targets for enhanced systems

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Bench / Pilot-Scale Research Actions

- Verification study
  - Chlor/dechlor reaction kinetic models research has been completed
- Site-specific validation study
  - Determine limits of technology effectiveness using site-specific conditions
  - Determine operating ranges for inactivation as function of dose and contact for meeting existing BADCT standards for alternatives
  - Determine operating ranges for inactivation of specific target organisms for alternatives
  - Determine operating ranges for inactivation efficiencies as function of WET requirements
  - Determine limits of technology enhancement, such as applying mixed oxidants
  - Establish confidence interval statistics for comparison with research literature

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Bench / Pilot-Scale Research Results

- Establish N fractionation: monochloramine/dichloramine formation
- Establish disinfection efficacy using varying levels of nitrified effluent
- Verify impact of bacterial re-growth potential
- Determine dechlorination efficacy in eliminating toxicity
- Confirm the most effective Cl:N weight ratio for germicidal response
- Define Methods of Analysis

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Full-Scale Confirmation Actions

- Validation Study
  - Chlor/dechlor reaction kinetic model calibrations/validations and operational configurations using pilots have been completed
- Site-specific Confirmation Study
  - Review and analysis of historical performance data from existing systems
  - Determine performance limits of existing systems as a function of operational limits of existing equipment
  - Develop and run tests for enhancements to existing system to meet BADCT
  - Develop statistical confidence intervals for enhanced conditions to equal or exceed current BADCT
  - Conduct in-situ hydraulic studies to confirm limits of flow dynamics in achieving contact times and mixing requirements
  - Prepare recommendations for system improvements based on in-situ confirmations of literature reviews and bench studies

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Full-Scale Confirmation Results

- Establish qualitative/quantitative mixing energy and mixing regimes in contact chamber
- Establish the dispersion index, the t_i and the modal time, t_p for existing conditions
- Derive the preferred L:W and H:W ratios for existing geometry
- Determine wind impacts on surface currents that impact short-circuiting
- Determine limitations of existing chlor/dechlor systems for disinfection performance
- Stress tests of existing delivery systems to simulate enhancements for disinfection efficacy
- Document disinfection efficacy simulations for enhanced chlor/dechlor

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Alternative Chlorine-Based Disinfection

- With chlorine addition:
  - Use of mixed oxidants
    - Hydrogen peroxide
  - Other

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Study Objectives

- Prove BADCT compliance with enhanced chlorination/dechlorination
- Develop report for ADEQ review and acceptance

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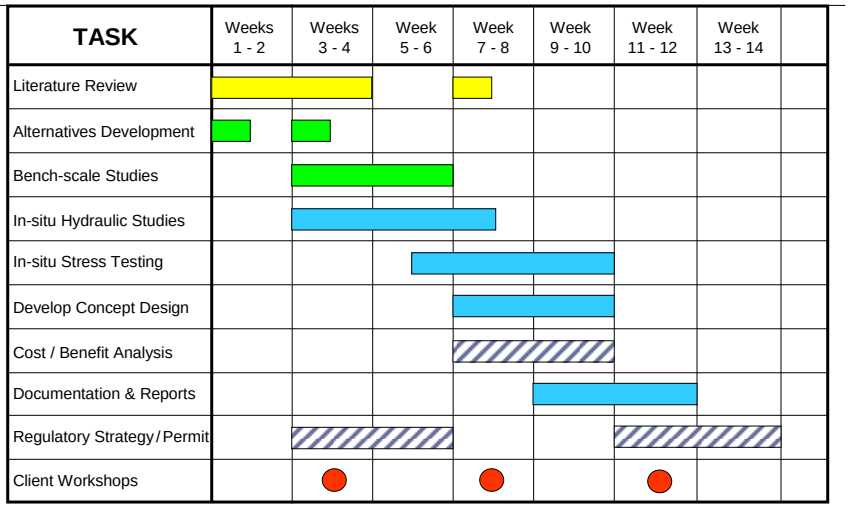
Report Summaries / Deliverables

- Documentation of literature review for existing and enhanced processes for compliance
- Documentation of bench testing and methods
- Documentation of full-scale testing and analyses and statistical variations
- Documentation of recommendations for full-scale system enhancements

45

Future Investigations Schedule



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Next Steps

- Assignments – who and what
- Schedule
- Next meeting

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Summary

Andy Richardson

Appendix G

Enhanced Chlorination / De-Chlorination

Workshop #2 – May 23, 2007

Enhanced Chlorination/De-Chlorination Evaluation
Literature Review and Findings
Meeting Notes

1. Enhanced Chlorination/De-Chlorination Evaluation Workshop No. 2 regarding the future disinfection of the wastewater effluent was held on May 23, 2007. The agenda is attached. The following were in attendance:

PCWMD
Director
Michael Gritzuk
Deputy Directors
Jackson Jenkins
PCWMD Staff
Jim Doyle
Frank Gall
Byron McMillan
Jeff Prevatt
Prakash Rao
Helen Rhudy
Ron Riska, Project Manager
Mandley Rust
John Sherlock
Legal
Harlan Agnew
Chuck Wesselhoff

TUCSON WATER
Tucson Water Staff
Melodee Loyer
Wally Wilson

GREELEY AND HANSEN PROJECT TEAM
Jerry Bish
Art Umble
Larry Leong, Kennedy/Jenks
David Murray, Brown and Caldwell
Jennifer Phillips, MPI

2. Major topics of the workshop were:
   - Literature review of current disinfection performance/practices with regard to Pima County future operations
   - Current disinfection facilities assessment/performance

   A set of handouts were provided to each attendee of the workshop.

3. Attendees were welcomed to the workshop by Jerry Bish who introduced the workshop topics and presenters. The workshop topics included:
   - Literature Review and Analysis
   - Disinfection Facility Assessments
   - Laboratory Facility Assessments
   - Discussions / Clarifications / Debate
   - Next Steps

4. Art Umble presented the decision-making process that would lead either to, or away from the use if enhanced chlorination to meet future ADEQ BADCT disinfection requirements. The intent of the

process is for the group to come to a degree of consensus as a result of the information provided during the workshop.

5. Larry Leong summarized the issues related to regulatory framework for the Pima County facilities. He used information from Florida and California that have standards most similar to those in Arizona to illustrate how the permitting issues in these other states have progressed and how these are, or may become issues for Pima County.

   Issues of concern are:
   - Single sample maximums for fecal and E.coli with or without filtration and with chlorine and UV technologies
   - WET testing that relate to the presence or absence of chlorine residual, ammonia, sulfite and/or non-neutralized organochloramines
   - Increased chlorine dosages developing disinfection by-products such as THMs and HAA5s
   - Cyanide formation potential

   Issues of consideration in the future are:
   - Enteric virus removal for effluent discharge quality greater than Class A which is to be recharged into potable aquifers
   - Florida and California foresee possible standards for *Cryptosporidium* and *Giardia* and enterovirus for water recycling, lower DBP standards (including NDMA) than currently applied to drinking water, and endocrine disruptors.

6. A survey of disinfection practices of major POTWs in the United States was correlated with those plants that use the Bardenpho process of comparable size to the future Pima County facilities. The key to this information was relating the disinfection practice associated and treatment process to the number of permit violations that have been reported. For plants that practice chlorination followed by filtration, the majority of violations correlated with failure to meet a single sample maximum criterion, or a WET test failure.

7. An overview of the data provided by Pima County from January 2004 through April 2007 was presented by Larry Leong. By using a frequency distribution statistical technique, observations from the analysis of the data revealed:
   - Fecal coliform and E.coli follow a log-normal distribution
   - 1.5 logs additional removal is necessary to achieve the 4-day non-detect criterion
   - 2.0 logs additional removal is necessary to achieve the single sample maximum for fecal coliform of <23 cfu/100 mL
   - 2.2 logs additional removal is necessary to achieve the single sample maximum for E.coli of <15 cfu/100 mL
   - 2.5 logs are needed for current Ina Road influent

   It was noted that driving much of the "upper removal" requirements is the presence of several "high" values for fecal and E.coli present in the data set provided. If these few points are removed from the data analysis, the higher log removal needs may actually turn out to be less. If the four maximum points were removed from the data analysis, it is likely that the amount of log-removal needed would be more in the range of that necessary to achieve the 4-day non-detect.

8. To set the stage for a potentially successful enhanced chlorination process design, two studies will need to be conducted. The first relates to determining the disinfection kinetics for the Ina Road BNRAS treated effluent. This study is performed in the laboratory using samples from the mixing chamber immediately following chlorine injection and held for various periods of time to simulate periods of chlorine contact, i.e., required CT. This will establish the CT required for compliance with future BADCT disinfection requirements. This study establishes the relative rate of inactivation and is a direct function of mixing regime. If the resulting kinetic analysis indicates that inactivation follows a first order relationship, then perhaps filtration is not needed at Ina Road WPCF. But if the declining rate of inactivation demonstrates more of a "knee" response, then filtration may be necessary. It is important that this set of data take into account the effect of suspended solids. This test could likely be accomplished within 3 months.

   The second study will attempt to establish the "actual" log-removal being achieved at the Ina Road facility by characterizing the influent/effluent fecal and E.coli concentrations. This will determine the total logs of removal necessary to meet the 4 days of non-detect out of 7 days. If more than 6 logs are found to be needed, then it may be concluded that enhanced chlorination is not likely the appropriate disinfection process for Pima County's facilities. However, if less than 4 logs are necessary, then enhanced chlorination will likely be appropriate without filtration. If it turns out to be somewhere between 4 and 6 logs, filtration may be needed if chlorination is applied. This study is especially critical with respect to the apparent seasonal variability that is seen in the existing data from 2004 to 2007. This second study would best be conducted over a 6-month period in order to gain the insights into the seasonal variations.

9. David Murray presented summaries of the observations of the existing chlorination facilities at both Ina Road WPCF and Roger Road WWTP, with focus on the former. These included hypochlorite feed systems, initial mixing systems, instrumentation and control systems, contact basin geometries, de-chlorination feed systems, and system hydraulics. He provided data on chlorine contact basin contact times and CT versus flow rate based on theoretical relationships. For the BNRAS (east) plant at Ina Road, there is a theoretical total CT of 230 mg-min/L and 160 mg-min/L for flow rates of 7 and 10 MGD, respectively, and 120 mg-min/L for a flow rate of 12.5 MGD. These values included the additional contact time achieved in the outfall pipeline from the contact basin prior to de-chlorination. Because the BNRAS plant operates in a full nitrification mode, the chlorine residual is predominantly free chlorine, thus indicating that the system operates at or above breakpoint.

   For the HPO (west) plant, the approximate CT for flow rates of 9 and 34 MGD are 180 and 30 mg-min/L, respectively. Total chlorine residual is made up mostly of combined chlorine, implying presence of ammonia in the final effluent.

   To establish a basis for design criteria for an enhanced chlorination system, specific field studies were proposed for the BNRAS (east) chlorine contact basin. The first of these would be a tracer study to establish the actual modal contact time in the chlorine contact basin. The tracer analysis provides evidence of hydraulic inefficiencies within the chlorine contact basin reflective of geometric configurations. The modal contact time would be what would be applied to the CT calculations for design modifications to improve and maximize contact basin performance.

To develop a more representative data set for establishing the parameters for a basis of design, operating the BNRAS plant outside of its currently operated "flat-lined" condition (currently operating around a constant 10 MGD flow) is encouraged during the aforementioned study.

10. Jennifer Phillips presented a review of the observations made of the existing laboratory facilities. Of primary concern is the limited incubator space available for the studies described above. The laboratory staff recommends that COD rather than BOD, and E.coli rather than fecal coliform tests be run to minimize incubator space requirements. It will be necessary to ensure that a chlorine analyzer capable of reading low levels (below 100 ppb) be available for residual analyses.

11. Mike Gritzuk observed from the workshop discussions that there is an optimism amongst the PCWMD staff that meeting the BADCT disinfection requirements using a chlorination process is feasible. He raised the question: Is it necessary to fully "bullet-proof" the system (such as with using a UV with filtration), or, is the PCWMD willing to accept infrequent microbial maximums and address consequences thereof if encountered?

    Jeff Prevatt stated his confidence in meeting the microbial standards. Recent test results at the chlorine contact basin for the BNRAS (east) plant indicate greater than $1x10^6$ concentrations entering the chlorine contact tanks and less than $5x10^0$ concentrations exiting, resulting in a 5.5-log removal. From this data he believes the issue for Pima County will be meeting the chlorine residual standard in the permit. His evidence is the initial results for the log removal levels on the influent versus effluent of the BNRAS chlorine contact basins.

    Jim Doyle challenged the team's interpretation of the TSS and corresponding microbial data that illustrates an inverse relationship. He stated that the data was not representative of the specific time of day that samples are taken and the respective chlorine dosages applied at those times. He believes that if this were taken into account, results would not show this type of correlation. The team responded in that the data provided to them for analysis was that which the laboratory collects and analyzes daily, and this analysis was reflective of the data in the reports.

12. The group reached consensus that the enhanced chlorination process is appropriate for the PCWMD facilities, but that additional studies be conducted to generate the additional information needed to confirm the log removal requirements, and to establish a set of parameters to support a basis of design for the preliminary design of system upgrades, improvements and modifications to the existing system at the Ina Road BNRAS plant, and for new systems PCWMD plans to construct to replace the HPO (west) plant and the existing Roger Road plant. Implications are that the design criteria established and operations and control strategies developed would then apply to both treatment plants.

    It was agreed that the team would establish a scope of services for PCWMD to consider for these additional studies. It was agreed that these additional studies would be conducted over a three month period beginning as soon as practical. In the meantime, the Ina Road operations staff would begin looking at what is needed to operate the BNRAS system in a more normal diurnal mode (assuming that the equipment and controls necessary will be able to be placed in service without delay). The team was also asked to provide specific information to the PCWMD laboratory staff on the type and

number of analytical tests that will be necessary to complete the study. Further , the team was asked to investigate the possibility of an outside laboratory to provide all microbial testing services necessary to complete the laboratory portion of the studies.

Agenda
Enhanced Chlorination/Dechlorination Disinfection Process Review
May 23, 2007

Time	Topic	Presenter
1:00 pm	*Outlying Facilities Offices –4527 W. Walker Road (near intersection of Ina Road and I-10)*	
1:00 pm	Opening Session	Art Umble/Jerry Bish
	• Welcoming Remarks	
	• Review Agenda	
	• Program Goals	
1:45 pm	Literature Review	Larry Leong
	• BADCT: Other states and Arizona	
	• Comparable Facility Requirements and Performance	
	• System Performance With and Without Filtration	
	• Standards and Design Criteria: Can they be met?	
	• Implications of WET	
2:45 pm	*Break*	
3:00 pm	Operations Data Overview	Dave Murray
	• Review of Physical Systems	
	• Can Existing System Limitations Be Defined?	
	• Existing System Performance (data analysis)	
	• Existing System Deficiencies for Meeting Standards	
4:15 pm	Questions/Discussion	ALL
4:40 pm	Next Steps	Art Umble
	• Actions	
	• Schedule	
4:50 pm	Summary/Wrap-up	Art Umble
5:00 pm	Adjourn	

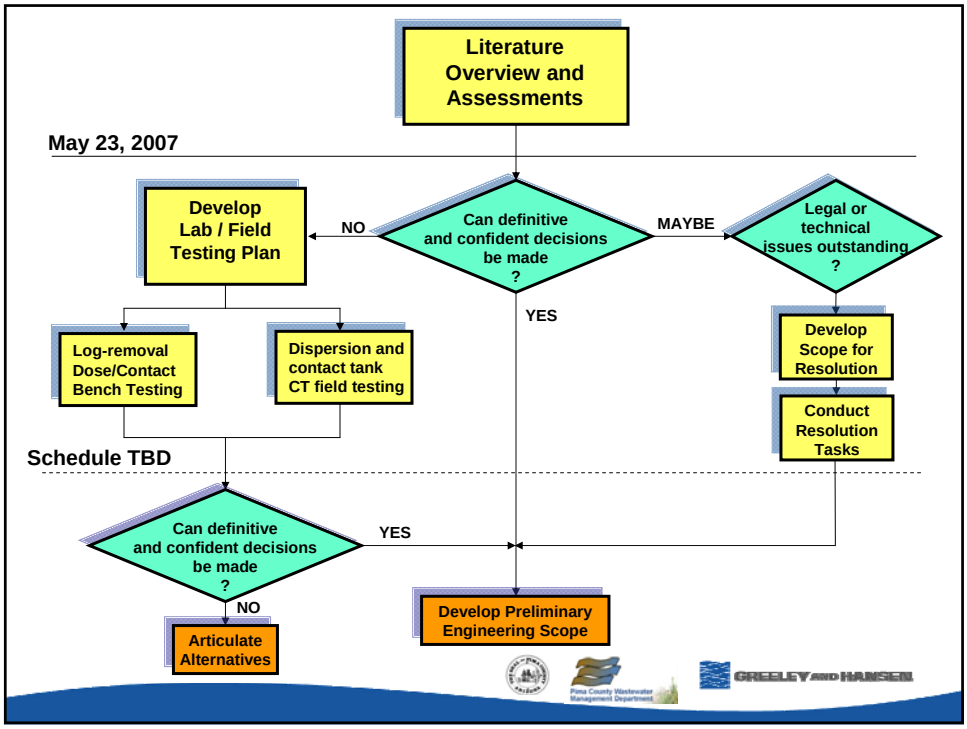
WORKSHOP:
Disinfection Process Review

Pima County Wastewater Management Department

May 23, 2007

Pima County WMD Program Goals

- Meet the BADCT Standards
- Meet a Class A+ Effluent Quality Discharge
- Minimize necessity of a $70M Expenditure if Filtration/UV is Req'd



WORKSHOP AGENDA May 23, 2007

- Part 1: Literature Review
- Part 2: Disinfection Facility Assessments
- Part 3: Laboratory Facility Assessments
- Discussions / Clarifications / Debate
- Next Steps

Part 1: Literature Review

Larry Leong
Kennedy/Jenks Consultants

Organization of Literature Review Discussion

- BADCT, FL and CA regulations
- Enhanced chlorination issues
- Survey of practice
  - Disinfection
  - Bardenpho
- Estimated additional removal
- Proposed studies

Regulatory Review

AZ Title 18 - BADCT, APP, NPDES, Reclamation Rules w/B+ Treatment

- FC/*E. coli* limits
  - ND in 4 out of 7 samples per week
  - Single sample < 23 FC/100 ml or < 15 *E. coli*/100 ml
- TN <10 mg/l
- Disinfection byproducts
  - 0.1 mg/l Total THMs with 0.08 mg/l as Alert Level
  - Cyanide ?
- WET
- Chlorine

Florida Regulatory Framework Chapter 62

- Surface water disposal
  - Secondary treatment – 20/20 BOD/TSS
  - High-level disinfection
  - No degradation of background water quality
- Reclamation, discharge to potable water supplies
  - High-level disinfection
  - <10 mg/l TN
  - MCLs<specified for community water systems

Florida's High-Level of Disinfection

Chlorine contact tank Influent (FC/100 ml)	Required CT (mg/l•minutes)	Logs Removal (%)
≤1000	At least 25	3 (99.9)
>1000-10,000	At least 40	4 (99.99)
>10,000	At least 120	>4 (>99.99)

- Max TSS < 5 mg/l, 30 day period, chlorine contact tank influent
- 75 percent, ND in 30 day period
- Max sample in 30 day period, <25 FC/100 ml

California Regulatory Framework Title 22 – Purple Book

- CA regulates total coliform and enteric viruses
- Defines different TC treated water
- Constrains water use and imposes conditions

Applicable CA Treatment Goals

- Disinfected secondary-2.2 recycled water
- Disinfected tertiary recycled water

Secondary - 2.2 Recycled Water

- 7 day median <2.2 Total Coliform (TC)/100 ml
- 1 sample can exceed 23 TC/100 ml in 30 day period with max <240 TC/100 ml

Secondary-2.2 Recycled Water

- Surface irrigation of food crops where edible portion is produced above ground and not contacted by recycled water

Tertiary Recycled Water

- Filtered effluent
- CT of 450 mg/l•minutes with modal contact time of >90 minutes on peak dry weather design flow
- Demonstrated disinfection technology that removes 5 logs of Ms2 or polio virus
- 7 day median <2.2 TC/100 ml
- 1 sample can exceed 23 TC/100 ml in 30 day period with max <240 TC/100 ml

Tertiary Recycled Water

- Edible root crops where the recycled water contacts edible portions
- Parks and playgrounds
- School yards
- Residential landscaping
- Unrestricted access golf courses
- Other irrigation not prohibited by CCR
- Groundwater Recharge Reuse Projects

Groundwater Recharge Reuse Projects

- Project requirements
  - Surface water spreading
  - Retained 6 months as groundwater
  - < 20 percent recycled water
- Water quality constraints on tertiary effluent
  - TOC < 16 mg/l (weekly 24 hr composite average)
  - <MCLs, SMCLs, notification levels for drinking water
  - TN < 5 mg/l with single sample maximum of 10 mg/l (blended water, weekly 24 hr composite average)

Permit Specified Microbes

- AZ – virus monitoring and limits for Class A and A+
- FL – *Giardia* and *Cryptosporium* for reuse/discharge to drinking water
- CA – virus monitoring, historically; *None* if using 5 logs removal technology defined by DHS

Enhanced Chlorination Issues

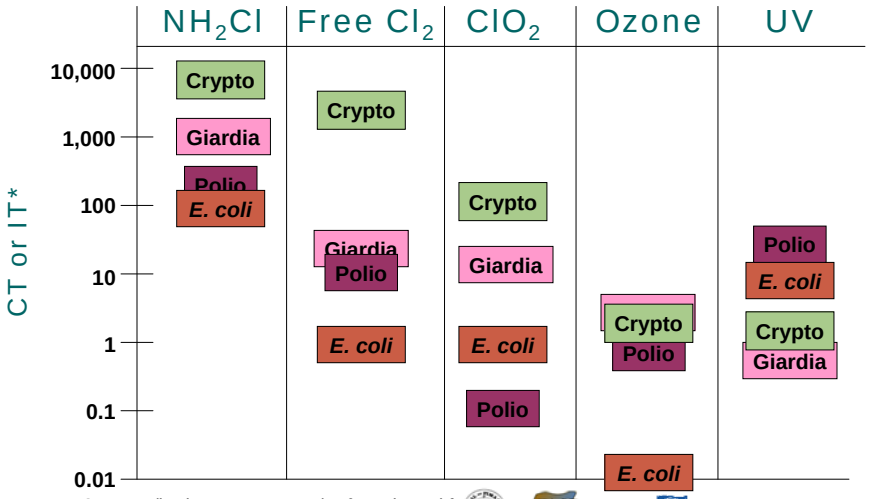
Current Issues

- > Max FC or *E. coli* with or without filters and with Chlorine and UV technologies
- WET testing – + for Chlorine and UV
  - Chlorine residual
  - Ammonia
  - Sulfite – oxygen?
  - Non-neutralized organochloramines (Blatchley, et al WERF 2005)
- Increased chlorine
  - Chlorinated DBPs (THMs & HAA5)
  - CN potential due to low limits, ~4 ug/l

Potential Future Issues

- **Arizona**
  - **Enteric virus for >Class A recharged into potable aquifers**
- **Florida**
  - ***Giardia*, *Cryptosporium* and enterovirus for recycling**
  - **lower THMs/HAA5 than for drinking water**
- **California - Groundwater Recharge Recycling**
  - **NDMA,**
  - **very low THMs/HAA5**
- **Others – endocrine disruptors, etc.**

Comparative Dose for 99% Inactivation in Drinking Water



*CT = mg/l*minutes IT = mJ/cm² Adapted from MWH, 2005

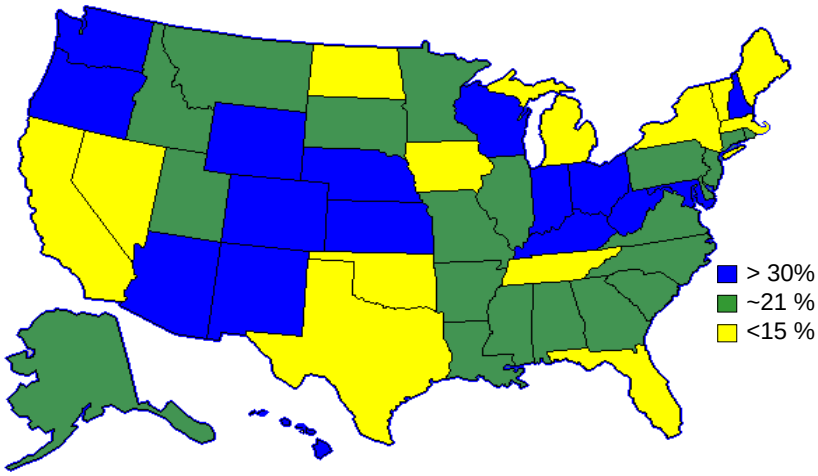
Survey of Practice

'06 US Profile of Major POTWs

(Total Major POTWs = 4,450)

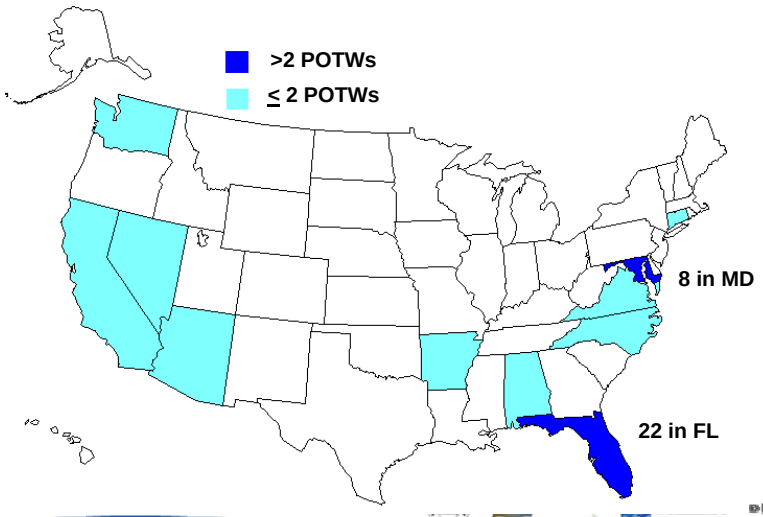
Disinfectant	Number	Percent
Chlorine	3,351	75.3
UV	930	20.8
Ozone	7	0.2
None	173	3.9

UV Disinfection at Major POTWs



45 Major POTWs Using Bardenpho

1-24 MGD, 27 % use UV



Profile of Similar Size for UV Disinfection and Bardenpho

Treatment Plant	Flow Range (MGD)	No. POTW	No. UV (%)	Bardenpho
Roger Road	22-42	149	25 (17%)	2 (22 & 24 mgd)
Ina Road	40-60	67	10 (15%)	0
Combined	72-92	18	1 (6%)	0

17 Major Bardenpho POTWs and Microbial Performance

Config-uration	Size (mgd)	No.	No. POTWs w/ Microbial Violations	
			Max	Average
UV	**17**	**1**	**1 (6)**	**0**
UV + Filters	**12,15**	**2**	**1 (2)**	**0**
Chlorine	**4-22**	**3**	**1 (1)**	**0**
Chlorine + Filters	**6-24**	**11**	**8 (25)**	**1 (1)**

( ) = total number of violations for category

17 Major Bardenpho POTWs and WET Performance

Config-uration	Size (mgd)	No.	No. POTW w/WET Violations	
			Flea	Minnow
UV	17	1	1	0
UV + Filters	12,15	2	1	0
Chlorine	4-22	3	1 (6)	1 (4)
Chlorine + Filters	6-24	11	10 (23)	5 (25)

( ) = total number of violations for category

THMs Violations at 7 POTWs

- Chlorine + Filters Config
- 37 total violations
  - 2 TTHM
  - 35 Single with 28 dichlorobromomethane
- Highly correlated with Max and WET violations (6 out of 7)

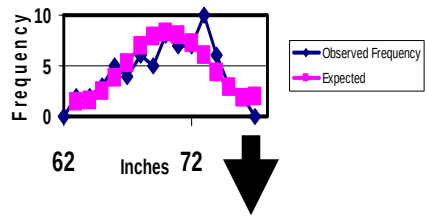
Phone Survey Highlights of 6

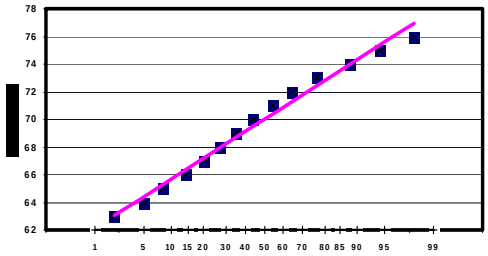
- No recollection of problems/violations after startup
- ~ 0.5-1 year to get plant under control
- Flotables/scum are issues
- High energy use, expanding using different treatment
- Filtration recommended for ≥ 4 ND

Estimated Additional Removal

Frequency Histogram to Linear Model

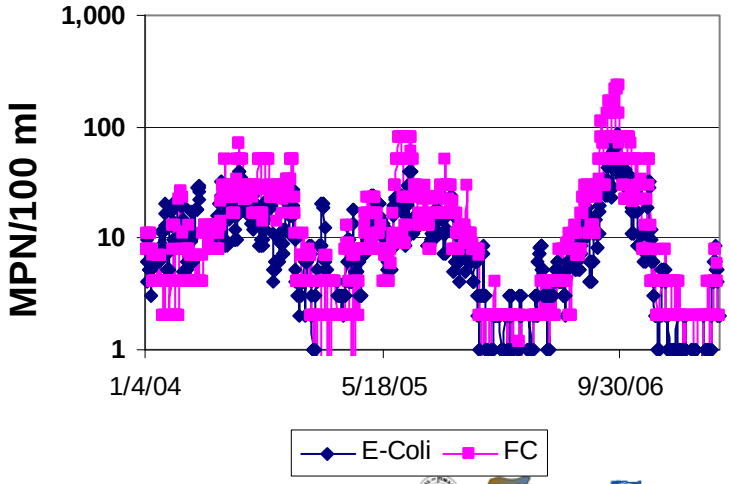
Height (in.)	Observed Freq	Expected Freq
63	2	1.51
64	2	1.53
65	3	2.5
66	5	3.79
67	4	5.28
68	6	6.96
69	5	7.85
70	8	8.34
71	7	8.09
72	7	7.18
73	10	6.01
74	6	4.28
75	3	2.9
76	2	1.79
77	0	1.97





Ina Road FC & *E. coli* Historical

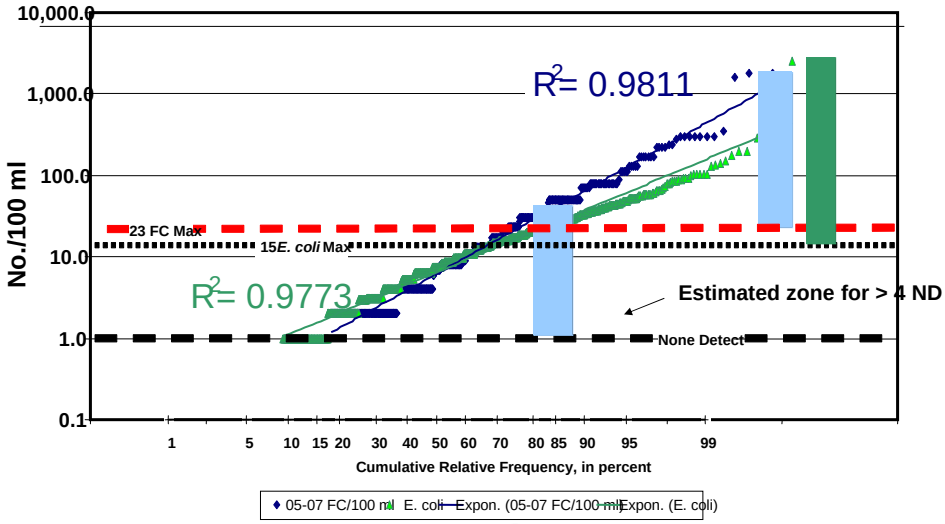
1 Jan 04 to 20 Apr 07



Convert to Frequency Distribution

- 1 Jan 04 to 20 Apr 07 FC and *E. coli*
- Determine frequency percent
- Plot and determine best linear fit

Estimated Removals to Meet BADCT



Results of Analysis

- FC and E. coli are log-normal
- ~ 1.5 logs needed for > 4 days ND
- ~ 2 logs needed for Max FC < 23
- ~ 2.2 logs needed for Max E. coli <15
- ~2.5 logs needed for current Ina Road influent, but Bardenpho influent likely to be lower than current

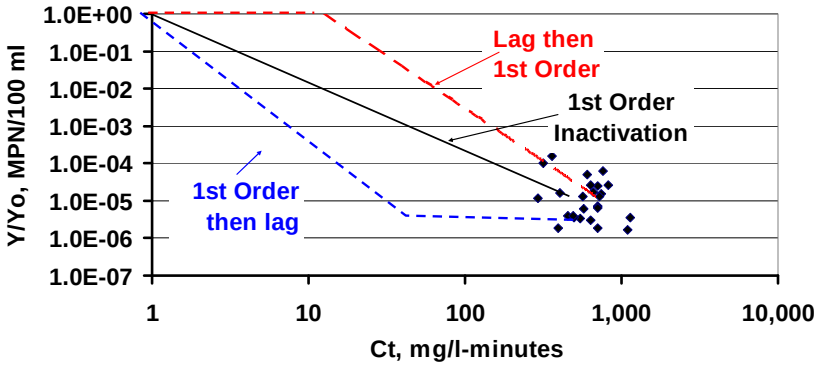
FC Removals for Different Secondary Effluent

Secondary Effluent	FC/100 ml	Estimated Removal to 4 ND (logs)
Activated Sludge	29,300	4.17 + 0.5 = 4.7
Nitrified AS	37,000	4.27 + 0.5 = 4.8
Biological Nutrient Removal	3,600	3.26 + 0.5 = 3.8

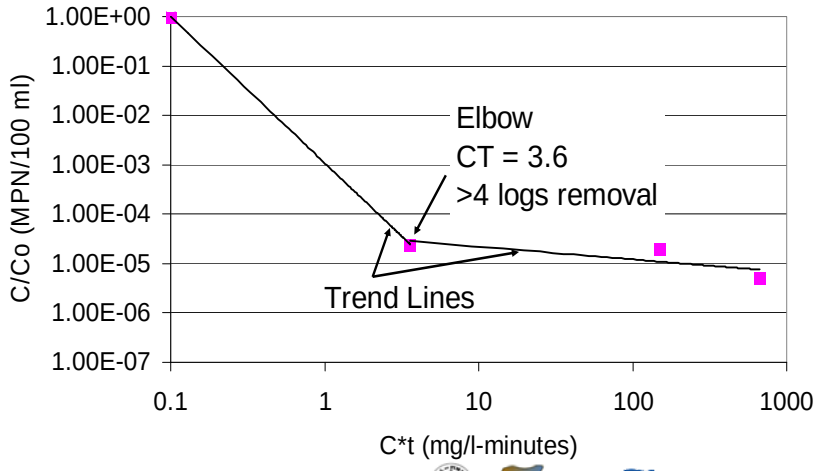
Rose, J., et al, WERF 2004

Proposed Studies

Potential Disinfection Kinetics

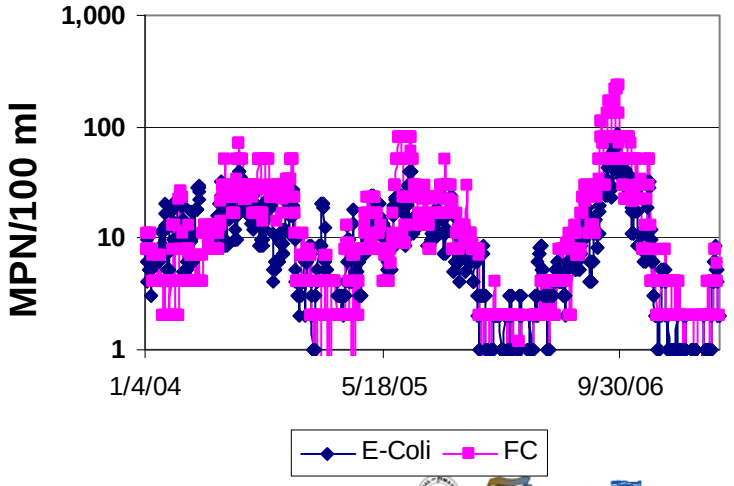


Full Scale California Study
First Order then Lag



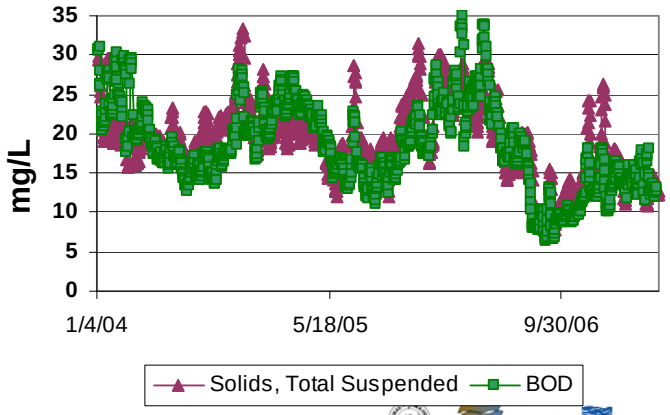
Ina Road Microbial

1 Jan 04 to 20 Apr 07



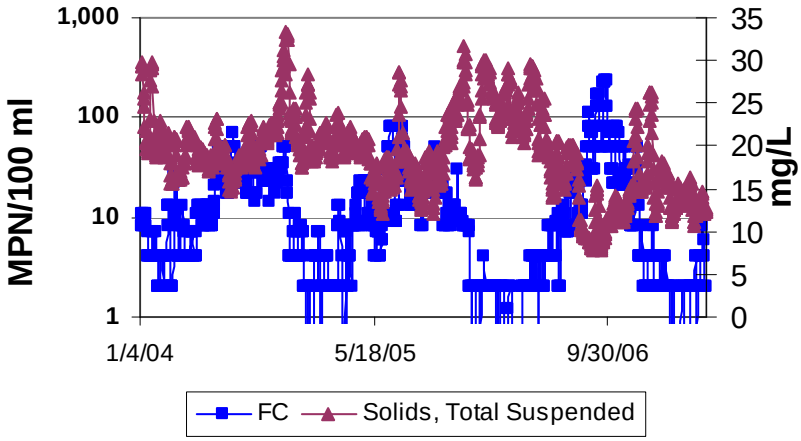
Ina Road BOD & TSS

1 Jan 04 to 20 Apr 07



Ina Road FC vs TSS

1 Jan 04 to 20 Apr 07



FC Historical Data

- Exhibits seasonality – winter & summer
  - FC peaks in summer
  - TSS peaks in winter
- TSS seems to have reverse correlation with FC, i.e., with high solids, lower chlorinated effluent FC

Proposed Bench & Field Studies

- Full-scale mixing with bench holding time to simulate chlorine contact tank (Study 1)
- Chlorine contact tank influent FC and or *E. coli* characterization (Study 2)

Study 1 Objectives

- Define BNRAS and therefore Bardenpho disinfection kinetics
  - If first order, perhaps filters not needed
  - If declining rate (elbow), perhaps filters may be needed
- Bench defines CT needed to meet BADCT

Study 1: Determine log-removals: Is there an elbow?

- BNRAS Effluent
- Full scale Water Champ mixing
- 0, 5 minutes, 30 minutes, 60 minutes holding times
- Analyze with 5 tube - 5 L, 100 ml, 10 ml for <0.02 FC MPN/100 ml reporting limit

Study 1 (cont.): Determine log-removals

- 5-7 trials per TSS conditions
- Normal and high TSS based on TU
  - Wait for high TU
  - Spike holding samples to simulate high TU
- Estimated time: 1-3 months depending on approach

Study 2 Objectives

- Determine seasonal variability of FC and *E. coli* concentrations
- Determine total logs removal to meet 4 ND
  - If > 6 logs needed, enhanced chlorine may not work
  - If <4 logs, perhaps without filtration may work
  - Something in between, filtration may need to be evaluated

Study 2: Characterize FC/*E. coli*

- 10-30 data points per scenario
- Potential scenarios
  - Seasonal – winter/summer
  - Plant performance – Low/high TSS
  - Others?
- Schedule – six months max

Pima County Wastewater Management Department

GREELEY AND HANSEN

Part 2: Facility Assessment

David Murray
Brown and Caldwell

Existing Disinfection Facilities

- Roger Road Facility
  - Sodium hypochlorite feed system
  - Contact basins
  - Initial mixing
  - Instrumentation and control
  - Dechlorination

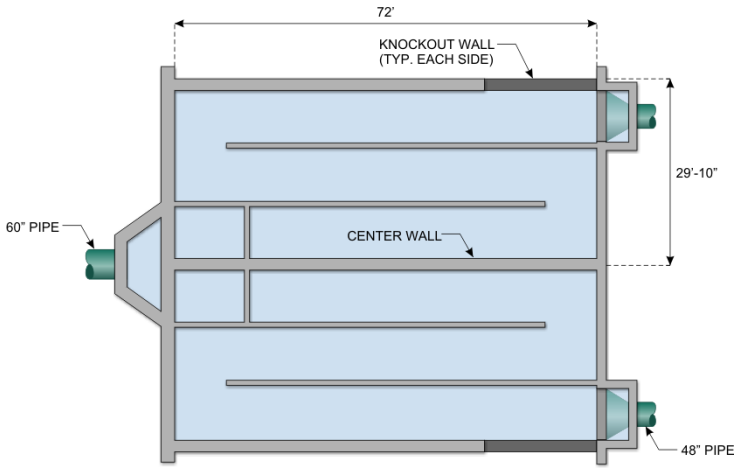
Existing Disinfection Facilities

- HPO (West) Plant
  - Hypochlorite feed
  - Initial mixing
  - Contact basins
  - Instrumentation and control

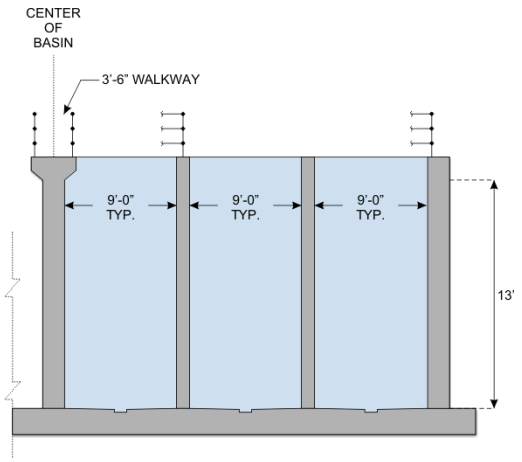
Existing Disinfection Facilities

- Ina Road BNRAS Facility
  - Hypochlorite feed
  - Initial mixing
  - Contact basins
  - Instrumentation and control

Ina Road East Chlorine Contact Basin – Plan

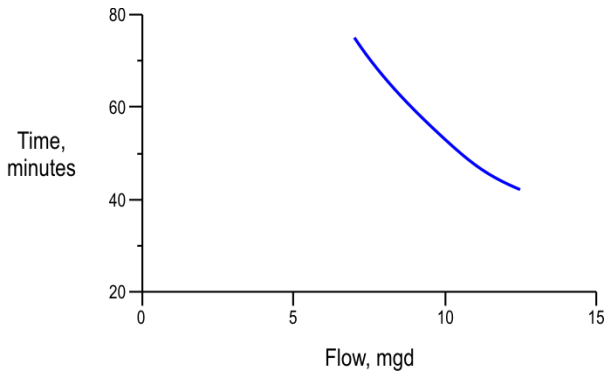


Ina Road East Chlorine Contact Basin – Cross Section

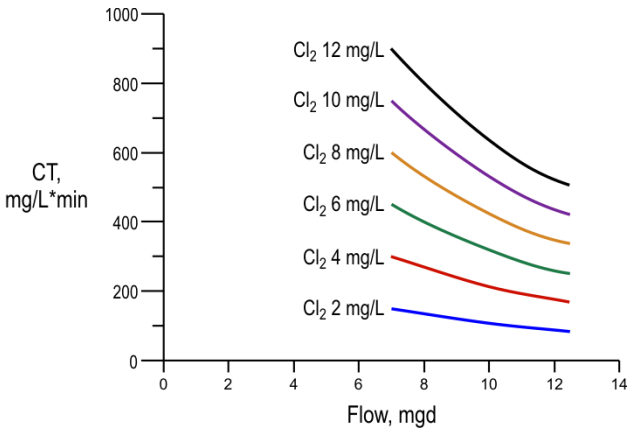


Existing Disinfection Operation and Contact Time

Ina Rd East (BNRAS) Plant CCB Contact Time vs. Flow Rate



Ina Rd East (BNRAS) Plant CCB CT vs. Flow Rate



Ina Rd East (BNRAS) Plant contact times

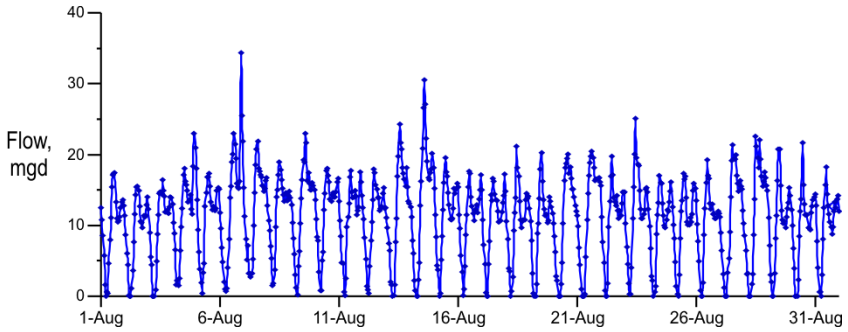
Flow (MGD)	7	10	12.5
Approx. chlorine residual (mg/L)[1]	2	2	2
Contactor residence time (min)	75	55	40
Pipe contact time (min)	40	25	20
CT in Contactor (mg/L*min)	150	110	80
CT in Pipe (mg/L*min)	80	50	40
Total CT (mg/L*min)	230	160	120

[1]Applied chlorine dose target is 2.5 mg/L

Summary of Ina Rd East (BNRAS) Plant operations

- Total chlorine residual primarily free chlorine
  - ammonia concentration ND
- Low initial chlorine demand
- Average residence times achieved in contactor
- Additional contact time in pipe flow prior to bisulfite quenching

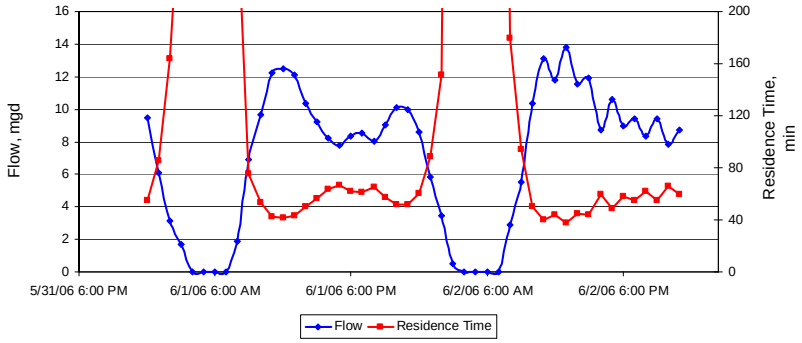
Ina Rd. West Plant theoretical flow



Assumptions;

- Total Flow **–** 12.5 mgd BNRAS **=** Ina Rd. West Plant Flow
- Wet Weather flow data from 2005
- 2005 total typical hourly flow values are representative of current flows

Ina Rd. West Plant CCB theoretical flow and residence time



Summary of Ina Rd. West Plant CCB flow and residence time

- Typical flows 8-12 mgd
  - 40 – 60 min residence time
- Max wet weather flow of 34 mgd
  - 15 min residence time
- 9 hours a day – flow less than 8 mgd
  - > 2 hr residence time
  - Stagnant
  - Great environment for microorganism growth

Ina Rd. West Plant contact times

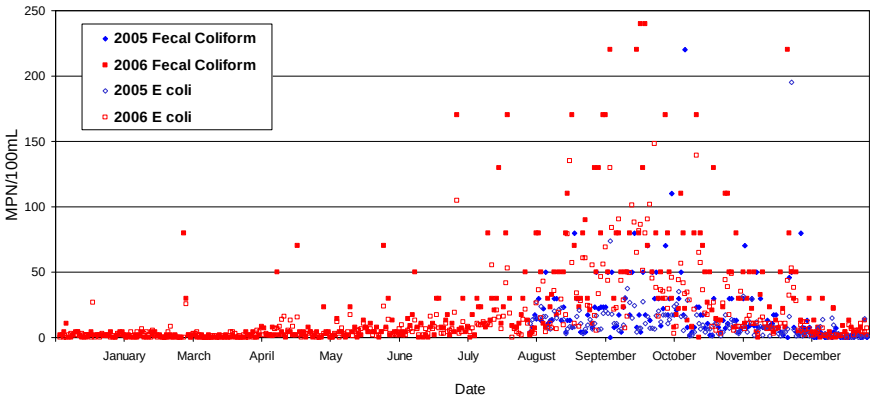
Flow (MGD)	9	34
Approx. chlorine residual (mg/L)[1]	2	2
Contactor residence time (min)	60	15
Approx. CT (mg/L*min)	180	30

[1]Applied dose approximately 6.5 mg/L with end residual of 1.7 mg/L

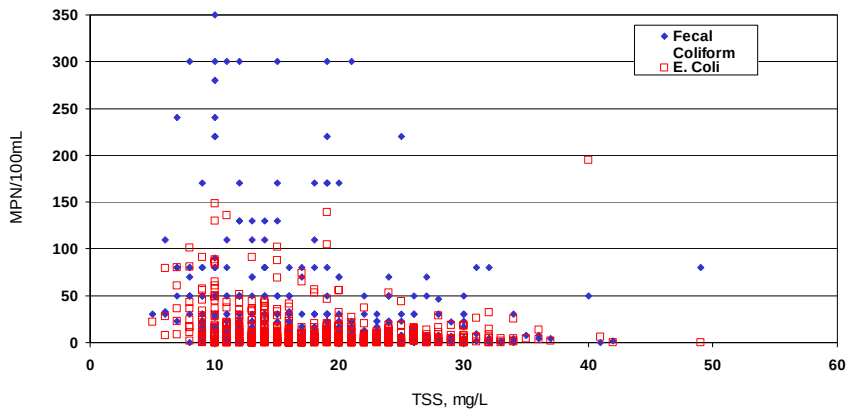
Summary of Ina Rd. West Plant Operations

- Low applied chlorine dose
- Total chlorine residual potentially mostly combined chlorine
  - Less efficient disinfectant
- Potential microorganism growth during lower flows
  - residual decay
  - microorganisms protected by TSS

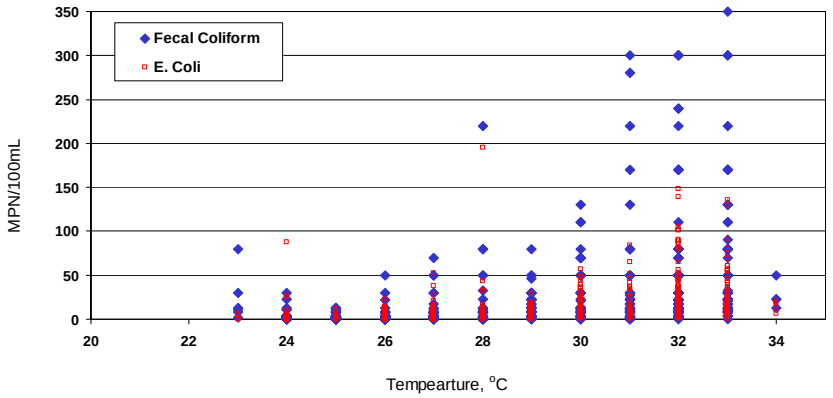
Fecal Coliform and *E. coli* concentrations increased in 2006



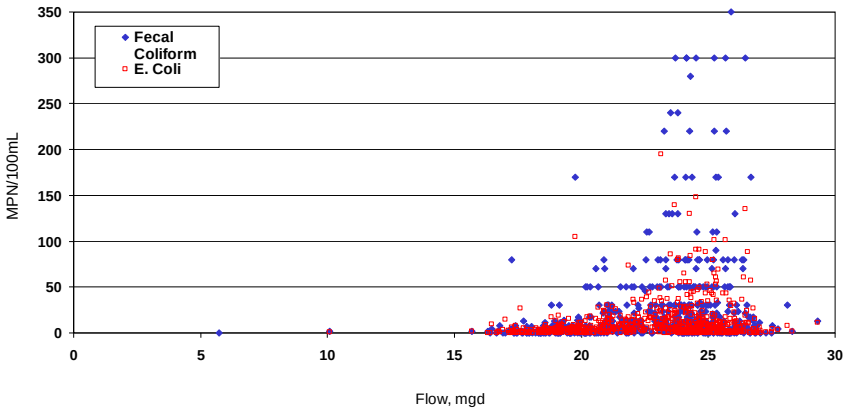
Fecal Coliform and *E. coli* versus TSS



Increase in Fecal Coliform and *E. coli* at higher temperatures



Increase in Fecal Coliform and *E. coli* at higher flows



Roger Rd. Plant contact times

Flow (MGD)	35	38	40
Approx. chlorine residual (mg/L)[1]	4.0	4.0	4.0
Contactor residence (min)	50	48	43
Contact time (mg/L*min)	200	192	172

[1] Approximately 6.0 mg/L applied chlorine concentration

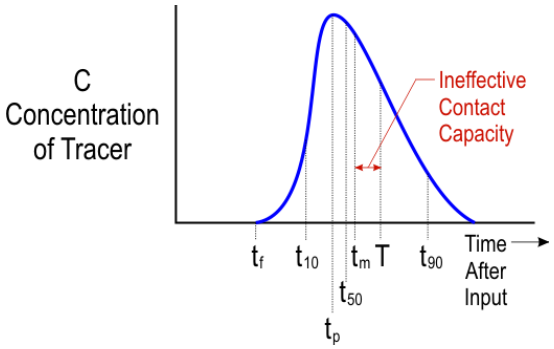
Summary of Roger Rd. operations

- Low applied chlorine dose
  - About 2 mg/L necessary to meet initial demand
- Total chlorine residual potentially mostly combined chlorine
  - Less efficient disinfectant
- Short residence time in contactors

Proposed Additional Studies

- Initial mixing optimization
- Contact basin dispersion
- Control optimization
- Chlorine residual/decay (volatilization) in contactor
  - Chlorine speciation

Contact Time Definitions



t_f = time at which the tracer first appears

t_p = time at which the peak concentration of the tracer is observed

t_{10} = time at which 10 percent of the tracer had passed through the reactor

t_{50} = time at which 50 percent of the tracer had passed through the reactor

T = the theoretical mean time

t_{90} = time at which 90 percent of the tracer had passed through the reactor

t_m = modal contact time

Initial Mixing Optimization

- To provide optimum contact between hypochlorite and influent to CCB
- Initial mixing should be as short and complete as possible
- Mixing can be evaluated with tracers

Contact Basin Dispersion

- Tracer studies to determine CCB efficiency
- Required to assess effectiveness
- Disinfection based on actual rather than theoretical contact time
- Can lead to basin improvements

Control Optimization

- Control by flow, oxidation reduction potential or chlorine residual
- Optimize placement of chlorine probes and sample points
- Can improve disinfection while reducing dose demand

Recommendations

- Identify chlorine concentration necessary to reach breakpoint chlorination (bench scale testing)
  - Each treatment plant
  - Determine combined vs. free chlorine concentrations
- Optimize current disinfection
  - Increase applied chlorine dose to achieve higher free chlorine concentrations
- Balance flow and chlorine concentration to Ina Rd. West Plant
  - Limit stagnant periods

Pima County Wastewater Management Department

GREELEY AND HANSEN

Part 3: Laboratory Assessment

Jennifer Phillips

Malcolm Pirnie, Inc.

Existing Laboratory Facilities

- Located at the Ina Road WPCF
- Comprised of three divisions:
  - Micro Lab
    - COD, BOD, TSS, F. Coliform, E. Coli, etc.
  - Nutrient Lab
    - Nitrate-N, Nitrite-N, TKN, ammonia-N, etc.
  - Organics Lab
    - Metals

Existing Laboratory Facilities

- Analyses typically completed within a week
- Lab reports available within two weeks
- QA/QC performed by a separate group
- QC check of analytical equipment - daily
- Calibration - quarterly

Existing Laboratory Facilities

- Incubator space limited
  - COD rather than BOD
  - E. Coli rather than Fecal Coliform
- Chlorine residual measured with HACH DR 2800
  - Manufacturer - specified Detection Limit = 10 ppb
  - Actual DL = 29 ppb (Method Detection Level study)
- On-line chlorine analyzer DL = 100 ppb
  - Cannot measure down to permit limits

Whole Effluent Toxicity (WET) Tests

- WET tests originally performed on-site
- 1999 waiver reduced WET test requirements
- Outside contract lab used presently
- Permit now requires increased WET testing
- County is considering resuming on-site WET testing

Use of Contract Laboratories

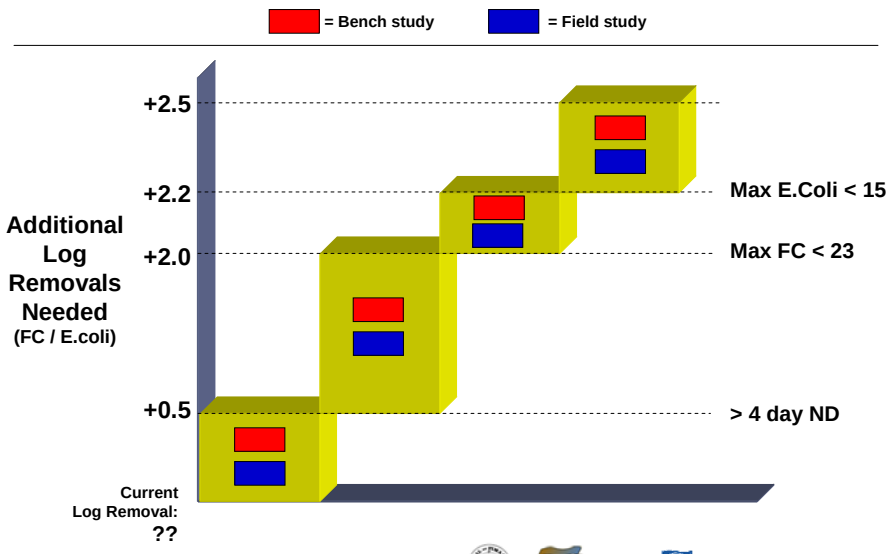
- Certified contract labs used
  - To relieve workload
    - Aquatic Consulting & Testing Inc., Tempe, AZ
  - For Whole Effluent Toxicity (WET) Testing
    - GEI Consultants, Inc., Littleton, CO

"Lab" Building at the Roger Road WWTP

- Located near the CCT
- Currently not in use
- Staff planning to use it as process control lab
- Has utility connections: Power, water, air, and possibly gas
- Could potentially be used for bench scale testing

Wrap Up & Summary

Enhanced Chlorination: with or without Filtration?



General Conclusions and Recommendations

OPINION:

- **Enhanced Chlorination has high probability of meeting the current BADCT**
- **Concern is high with Enhanced Chlorination meeting THM limits if free chlorine is dominant species**
- **Without Filtration:**
  1) **likely will meet 4-day non-detect**
  2) **potentially will not meet the FC and E.coli max**

SUGGESTED STUDIES/EVALUATIONS:

- **Gain confidence in understanding how the maximums can be met**
- **Provide information toward basis of design**

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Wrap Up

Questions

Discussion

Debates

Next Steps

Appendix G

Enhanced Chlorination / De-Chlorination

Workshop #3 – September 12, 2007

Enhanced Chlorination/De-Chlorination Evaluation
Laboratory and Field Study Results and Conclusions
Meeting Notes

1. Enhanced Chlorination/De-Chlorination Evaluation Workshop No. 3 regarding the future disinfection of the wastewater effluent in Pima County was held on September 12, 2007. The agenda is attached. The following were in attendance:

PCWMD
Deputy Directors
Jackson Jenkins
Mike Bunch
PCWMD Staff
Jim Doyle
Byron McMillan
Jeff Prevatt
Dave Bartos
Ed Jandali
Michael Kostrzewski
Mandley Rust
Ron Riska, Project Manager
Legal
Harlan Agnew

TUCSON WATER
Tucson Water Staff
Melodee Loyer
Wally Wilson

GREELEY AND HANSEN
Project Team
Jerry Bish
Art Umble
Larry Leong, Kennedy/Jenks
David Murray, Brown and Caldwell
Jennifer Phillips, MPI
Sam Jeyanayagam, MPI

2. Major topics of the workshop were:

- Review results from laboratory and field studies performed during July and August 2007
- Review implications of results in terms of BADCT compliance
- Review recommended improvements to existing BNRAS chlorine contact basin to enhance the disinfection efficacy
- Establish disinfection criteria for future facilities upgrades and expansions

A set of handouts of the presentation was provided to each attendee of the workshop. The following is a brief summary of the discussions and results.

3. Kinetics Studies

Results of the two studies conducted to examine the log inactivation of E.coli were presented. The basic conclusion was that the system is likely to meet the BADCT's requirement of 4 days of E. coli (or fecal) non-detects out of 7 days based on the current operational mode for the BNRAS plant, and the current chlorine contact basin design and operation of the chlorination injection system.

The challenge with the current system is consistently meeting the single sample maximum limits for E. coli of 15 colonies per 100 ml. If no improvements were made to the existing system, on average log inactivation achievable is greater than 4 logs. But under the system's "worst case" operating

condition (i.e., E. coli concentrations in the secondary effluent being at their maximum--based on measured data--at the same time the chlorine contact basin exhibits its poorest level of performance), this inactivation drops to 2.3. It is under this scenario that the system is vulnerable to a single sample maximum limits violation.
To reduce the vulnerability of single sample maximum violations, achieving a 5-log inactivation in the average condition is necessary. The kinetics generated by the modeled results indicate that greater than 5-log inactivation for an average is feasible. But since the field study data shows that only slightly higher than 4-logs are being achieved on average, this indicates that there is a strong possibility that the existing facility can be improved. Extrapolation of the kinetics results indicates that to achieve a 5-log inactivation, a CT of approximately 85 mg/L*min is needed. Achieving this means that adjustment to the chlorine (hypochorite) dosage and upgrades to the chlorine contact basin are necessary to boost the CT.

For purposes of conceptual design, a target of 100 mg/L*min will be used for any new chlorine contact basin construction at the metropolitan Pima County wastewater treatment facilities requiring disinfection. Upgrades in design features of the contact basins focus on two improvement areas: 1) mixing of the sodium hypochlorite into the bulk fluid, and 2) improving the plug flow nature of the contact basin. Modifications discussed related only to the existing BNRAS chlorine contact basin, but the basic modification requirements would apply to the high purity oxygen chlorine contact basin which is planned for use in the expansion and upgrades at the Ina Road WPCF. In the new, and expanded and upgraded facilities, provisions should be provided to modify the CT up to 450.

4. Field Studies

Results from two detailed field studies were presented. These were: 1) tracer results reflecting the mixing regime of the WaterChamp mixing in the influent chamber and the turbine mixers in the flash mix chambers, and 2) degree of dispersion of the plug flow as the flow travels through the contact basin. Results indicate that mixing in the influent chamber can be improved by adding a second WaterChamp unit and positioning these to more central points in the chamber. An alternative would be to use just one WaterChamp unit, but place it parallel to the influent flow with its injection discharge positioned upstream in the flow path.

PCWMD staff suggested that the team also consider use of a static mixing regime in the channel upstream of the influent chamber to minimize any need for modifications to the influent chamber or to the chlorine contact tank.

Upgrades to the flash mixing chamber include consideration of removing the mixers from service due to the significant degree of back-mixing that these mixers create, thereby dramatically reducing the plug flow efficiency in the channel.

Upgrades to the chlorine contact tank include placement of corner fillets, a longitudinal baffle in the first pass, and a perforated transverse baffle at the end of the first pass, all of which would improve the plug flow characteristics. Hydraulic head considerations must be examined before any of these options, particularly the perforated transverse baffle, are installed.

5. pH Shift

The concept of shifting the operational pH of the water was presented as an option to consider for improving the effectiveness of the disinfection strength. Though this option was not presented as a formal recommendation, it was suggested that the PCWMD staff may want to include this in their internal deliberations of measures to investigate for further improving the disinfection system performance. This could be a factor if and when disinfection by-products become a regulatory issue for Pima County.

6. Additional Studies Recommended

It was clarified for the attendees that the results of these studies did not address the implications of the enhanced chlorination process on whole effluent toxicity (WET) assays or on the formation of disinfection by-products (DBP). It was suggested that the PCWMD laboratory director consider conducting a series of bench-scale tests to determine what, if any, impact on the WET and DPB elevated levels of chlorine dose might create. It was also suggested that a set of jar tests be run to determine the probable levels of chlorine dose that will be necessary to support the CT = 100 mg/L*min target. It is likely that the dosage will be at least double (4 mg/L to 6 mg/L) what is currently practiced (2 mg/L) at the BNRAS facility.

7. Consensus

The project team, consisting of Larry Leong (Kennedy/Jenks Consultants), David Murray (Brown & Caldwell), Sam Jeyanayagam (Malcolm Pirnie), Jennifer Phillips (Malcolm Pirnie), and Art Umble (Greeley and Hansen) agreed unanimously on the conclusions of the studies and the proposed recommendations. The PCWMD staff present accepted the team's recommendations.

The project team will prepare a final report that summarizes the studies, results, conclusions and recommendations. Upon acceptance by PCWMD, this report will then become an appendix to the Regional Optimization Master Plan and the report recommendations incorporated into disinfection requirements for the new and expanded and upgraded facilities.

Agenda
Enhanced Chlorination/Dechlorination Disinfection Process Review
May 23, 2007

Time	Topic	Presenter
1:00 pm	*Ina Road WWTP Offices*	
1:00 pm	Opening Session	Jerry Bish/Art Umble
	• Welcoming Remarks	
	• Review Agenda	
	• Program Goals	
1:15 pm	Results of Kinetics Studies	Larry Leong
	• Data analysis	
	• Implication of results for BADCT	
2:00 pm	Velocity Profiles & Chlorine Residual Decay	Jeff Prevatt
	• Study results from tests on West HPO Plant CCB	
	• Results of E.coli inactivation study (August 2007)	
2:30 pm	Field Study Results	Dave Murray
	• Mixing analysis	
	• Tracer dispersion analysis	
	• Implications for BNRAS CCB	
3:15 pm	Recommendations for BNRAS CCB Upgrades	Art Umble
3:45 pm	Open Discussion	Jerry Bish/Art Umble
	• Consensus	
	• Next Steps	
4:00 pm	Adjourn	

WORKSHOP:
Enhanced Chlorination:
Field Studies – Protocols, Results, Conclusions

Pima County Wastewater Management Department

September 12, 2007

Overview of Workshop Purpose

- Review of Project Objectives
- How did we get to this point?
- Review of the Field Study Objectives
- What decisions need to be made today?

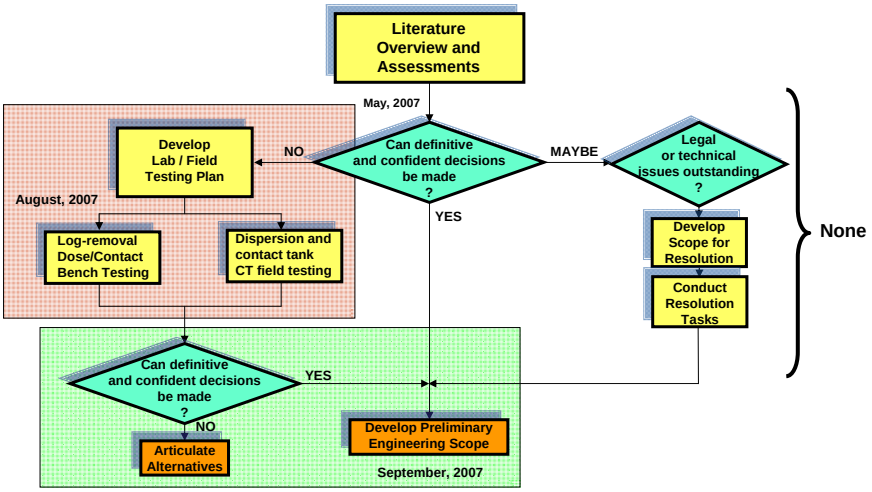
AGENDA

- Review of the Kinetics Analysis
- Review of the Field Study Results
- Overview of Opinion
- Overview of Recommendations
- Next Steps

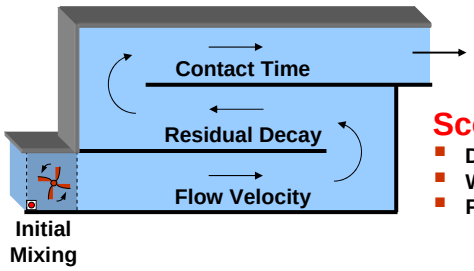
Review of Primary Objectives

- PCMWD intends to meet BADCT
- PCMWD desires to produce a Class A+ effluent quality
- PCMWD desires to eliminate the need for Filtration + UV because of the economic impact on the utility

Review of Decision Process



General Technical Approach



Scope Does NOT Address:

- Dechlorination efficiency
- WET "Reasonable Potential to Exceed"
- Formation of DBP

Scope Addresses Several Essential Questions

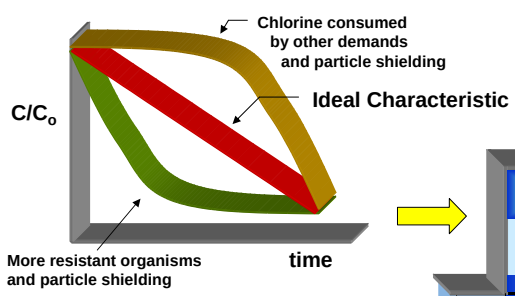
- What removal is required of the system to reach BADCT?
- What is the overall removal "capability" of the system?
- How do CCB physical characteristics relate to the disinfection efficiency?
- Can the physical system be modified to improve efficiency?

General Technical Approach

- Kinetics: What are the rate and characteristics of bacterial inactivation?
- Mixing Efficiency: How effective is the mixing energy at "breaking up" the particulates that shield organisms?
- Flow Efficiency: What is the relationship between the flow regime and the contact time of exposure?

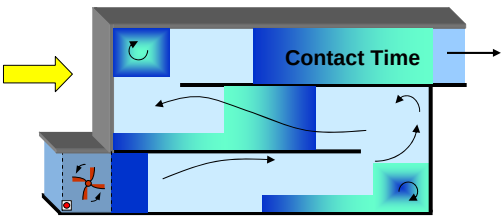
General Technical Approach

Rate and Characteristic of Inactivation



Fundamental Design Parameter

(C) x (T)



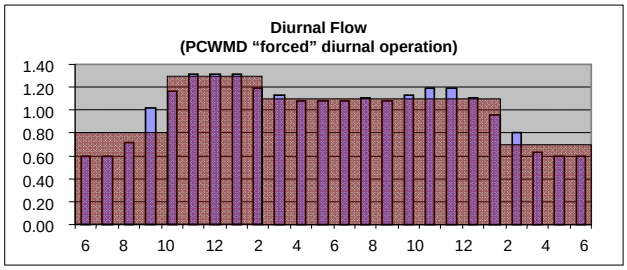
Dosage affects potential for exposure → inactivation

Mixing affects degree of dosage distribution → exposure

Flow regime affects dispersion → contact time

General Technical Approach

- Studies conducted under pseudo diurnal flow pattern through BNRAS



6AM – 10AM → $0.8Q_{ave}$
10AM – 2PM → $1.3Q_{ave}$
2PM – 1AM → $1.1Q_{ave}$
1AM – 6AM → $0.7Q_{ave}$

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Part 1: Kinetics Study – Protocol; Results; Conclusions

Jeff Prevatt
Larry Leong

Summarize Results

- Two Studies
  - Kinetic Study – Evaluation of Site Specific Disinfection Behavior
  - 27-Day Study – Determine Disinfection Removal Goals
- Observations, Recommendations

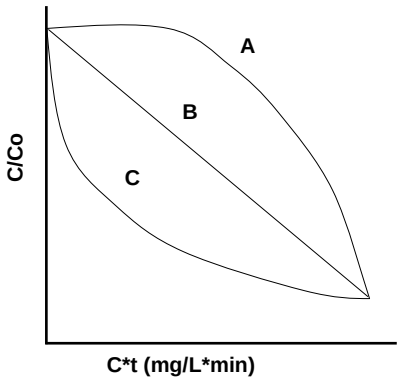
Kinetic Study*

- Sampling locations
  - Secondary Effluent
  - Collected replicate samples, just outside mixing chamber = 2.25 minutes @12.5 MGD
  - Held for 5 to 90 minutes, neutralized, then tested
- Determine Total Coliform and *E. coli* in triplicate
- Nine trials on different days

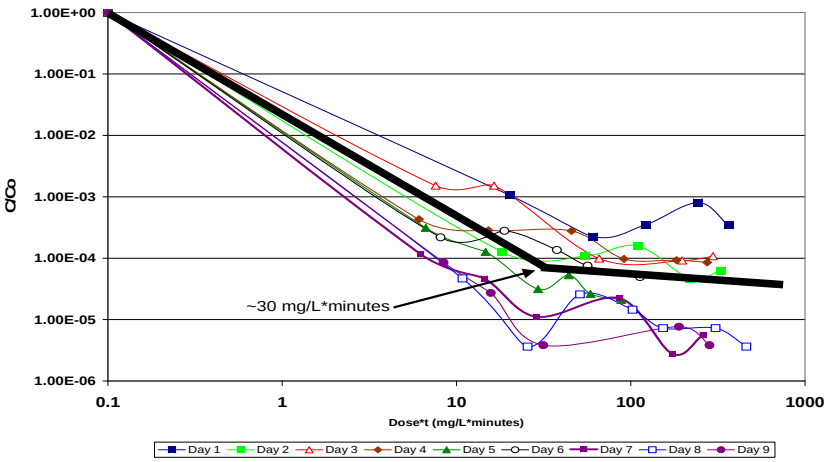
*PCWMD performed study

Typical Disinfection Kinetic Curves

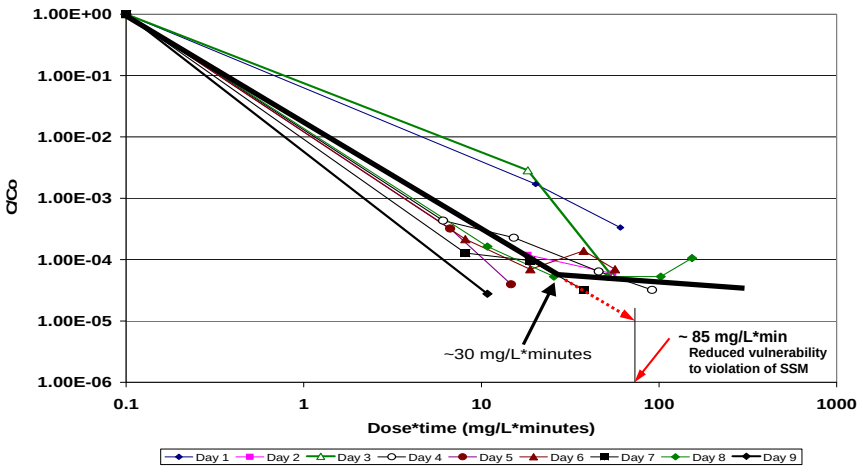
- A. Convex – initial lag
- B. Linear – 1st Order
- C. Concave
  - Multiple resistance
  - Clumps
  - Imbedded in particles or TSS



Total Coliform Kinetics



E. coli Kinetics



27-Day Study*

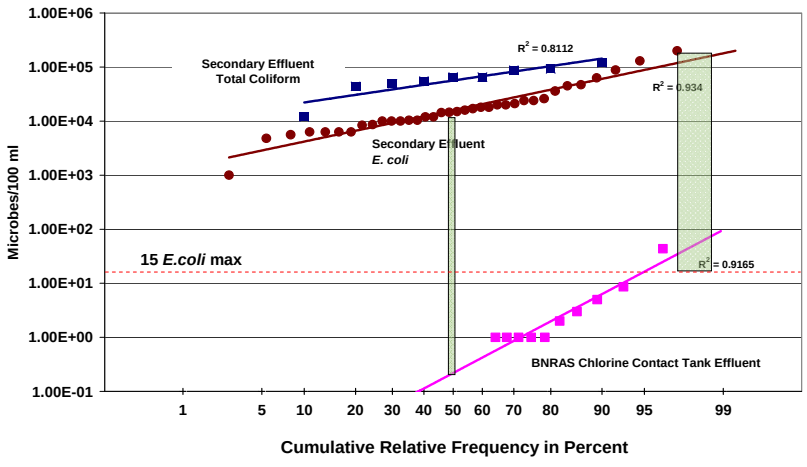
- 17 May to 10 July
- BNRAS base loaded @ constant flow
- Sampled at Secondary and Chlorinated BNRAS Effluent
- Tested for *E. coli*
- Evaluated observed & modeled results

***PCWMD performed study**

Modeling Approach

- Convert Data to Z Distribution
- Determine "average" removals
- Determine "extremes" of the distribution

BNRAS 27-Day Study



Four ND per Week Likely to be Met

- If reporting limit is 2 MPN/100 ml, 80 % of the time <2 with ~4.5 logs inactivation (modeled)
- 4 out of 7 = 57 % is BADCT req't
- Current BNRAS operations and contact basin design likely to meet 4 ND out of 7 samples per week

27-Day Observed Vs Modeled

Data Source	Samples	Median	Min	Max
E. coli detected in CCT Effluent (MPN/100 ml)	10	1.5	1	43.7
Observed Log Inactivation	10	4.05	2.29	4.26
Modeled Log Inactivation	10	>5	3	>5

These results indicate that bench-scale tests do not adequately represent the physical characteristics of the CCB…
…this implies that possibility of improving the full-scale system exists.

Meeting Max Limit may be Problematic

E. coli Max. = 15 microbes/100 mL
Fecal Max. = 23 microbes/100 mL

- From Kinetic Study
  - 200,000 = max *E. coli* observed and applying min kinetic log activation (3.5 logs) ➔ 66 *E. coli*

3.82 log is required for 95% meeting max

Meeting Max Limit may be Problematic

- From 27-day Study (under existing facility conditions)
  - 1 over *E. coli* Max out of 27 sample = 3.7 %
    For 365 days @ 3.7% ➔ 14 days of *E. coli* > Max*
  - 200,000 max *E. coli* observed + min log inactivation observed (2.29 logs) ➔ 1,025 *E. coli***

***This is based ONLY on a test performed in a 27-day summer condition**
****Worst case may be an unrealistic condition: highest secondary effluent *E.coli* coupled with lowest *E.coli* removal through disinfection (data does not reflect that this condition exists).**

Compliance Challenge for Meeting the Single Sample Maximum

Compliance Level (% of time)	Logs of Inactivation	Modeled Violations* of Max *E. coli* (Days/Year)
100	>4.12	0
95	3.94	18
90	3.7	36

***This is based ONLY on a test performed in a 27-day summer condition**
****Worst case may be an unrealistic condition: highest secondary effluent *E.coli* coupled with lowest *E.coli* removal through disinfection (data does not reflect that this condition exists).**

Study Vs Full Scale CCB Results

- 1.2 logs less inactivation by CCB at full scale
  - Min Kinetic Study = 3.5 logs removal
  - Min of full scale CCT = 2.29 logs removal
- This indicates that improvements to the CCB hydraulics (mixing and flow) may help provide the additional inactivation desired

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Part 2: CCB Chlorine Residual Decay Profile Results; Conclusions

Jeff Prevatt

Pima County Wastewater Management Department

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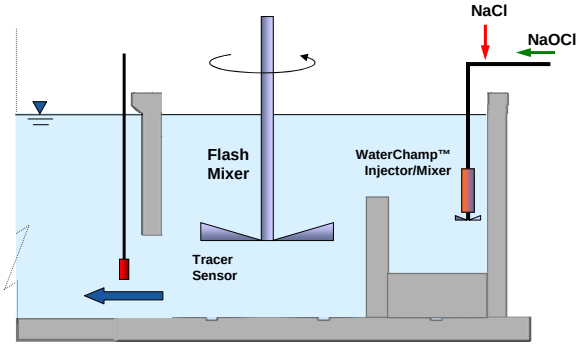
Part 3: CCB Velocity Profile Results; Conclusions

Jeff Prevatt

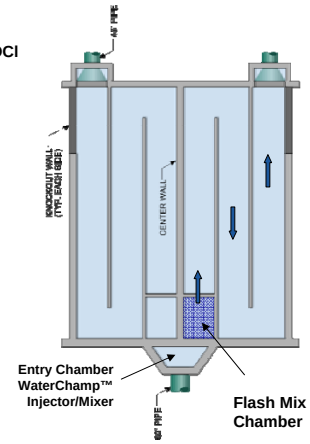
Part 4: Mixing Study – Protocol; Results; Conclusions

David Murray

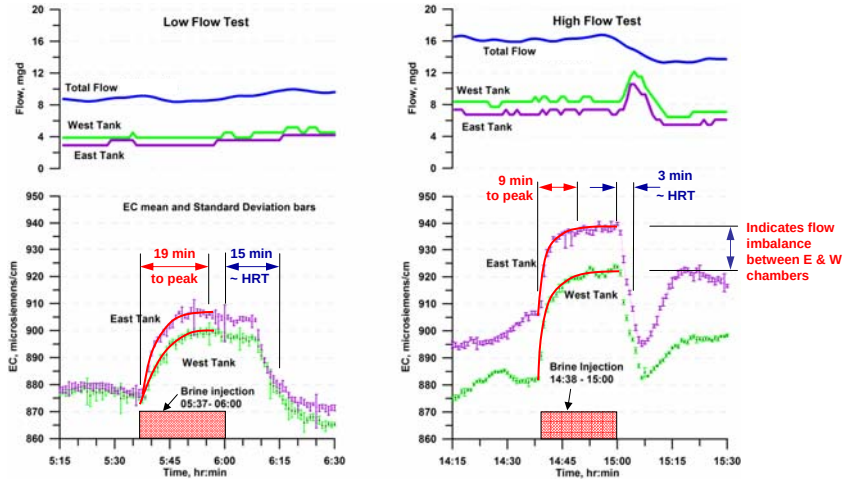
Disinfectant Mixing Analysis



Flash Mix Chamber



Disinfectant Mixing Analysis



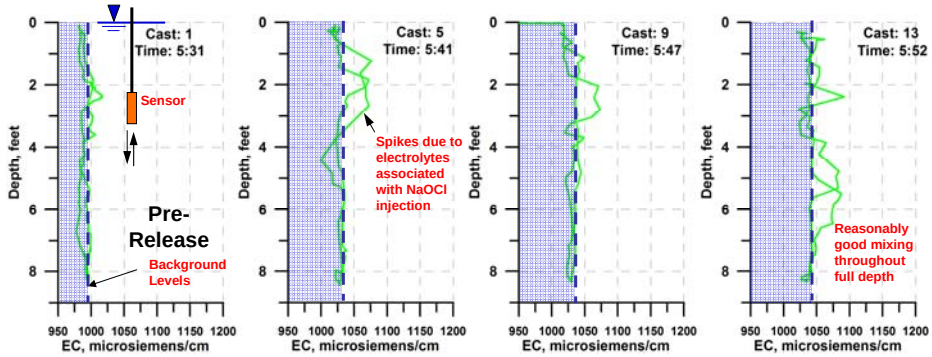
Mixing Analysis

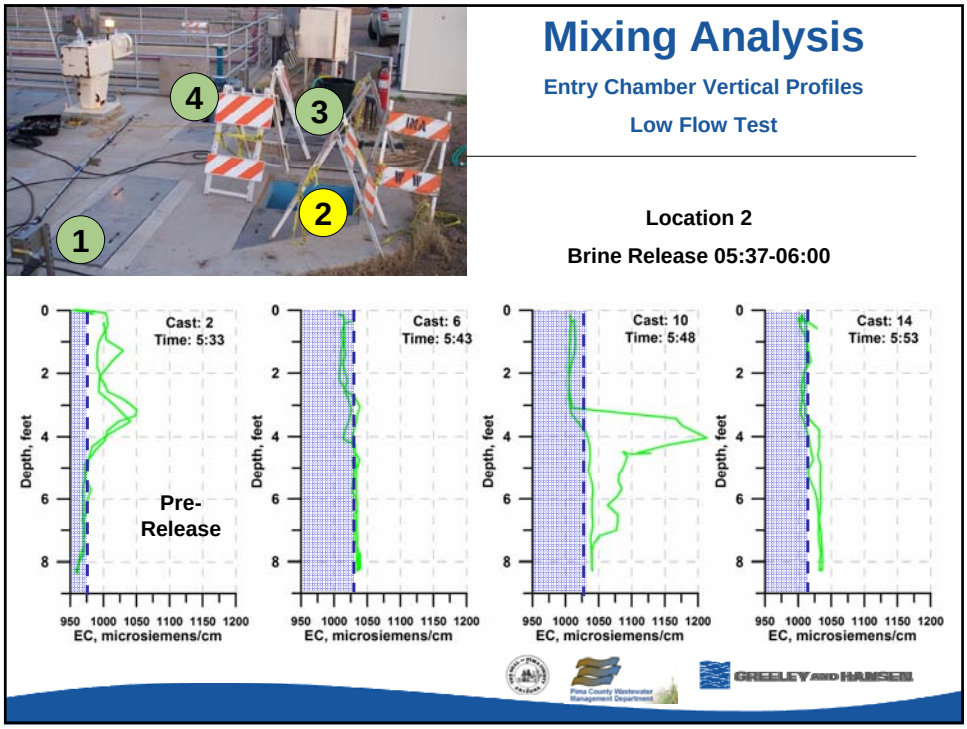
Entry Chamber Vertical Profiles

Low Flow Test

Location 1

Brine Release 05:37-06:00




Mixing Analysis
Entry Chamber Vertical Profiles
Low Flow Test
Location 2
Brine Release 05:37-06:00
4
3
2
1
Cast: 2
Time: 5:33
Pre-
Release
Cast: 6
Time: 5:43
Cast: 10
Time: 5:48
Cast: 14
Time: 5:53
Depth, feet
EC, microsiemens/cm
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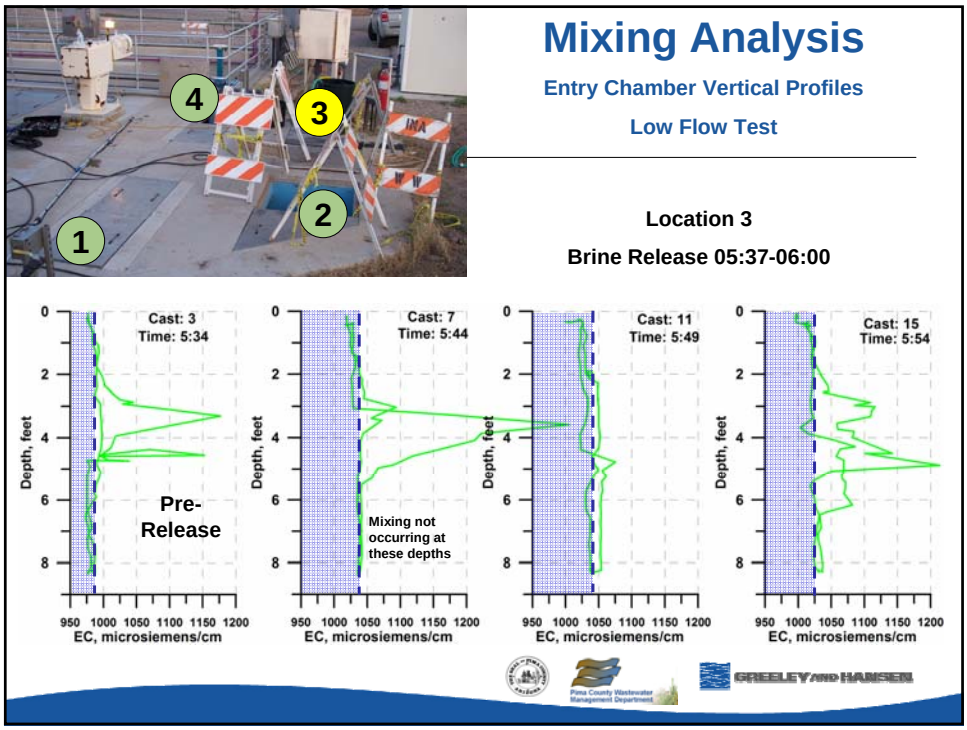
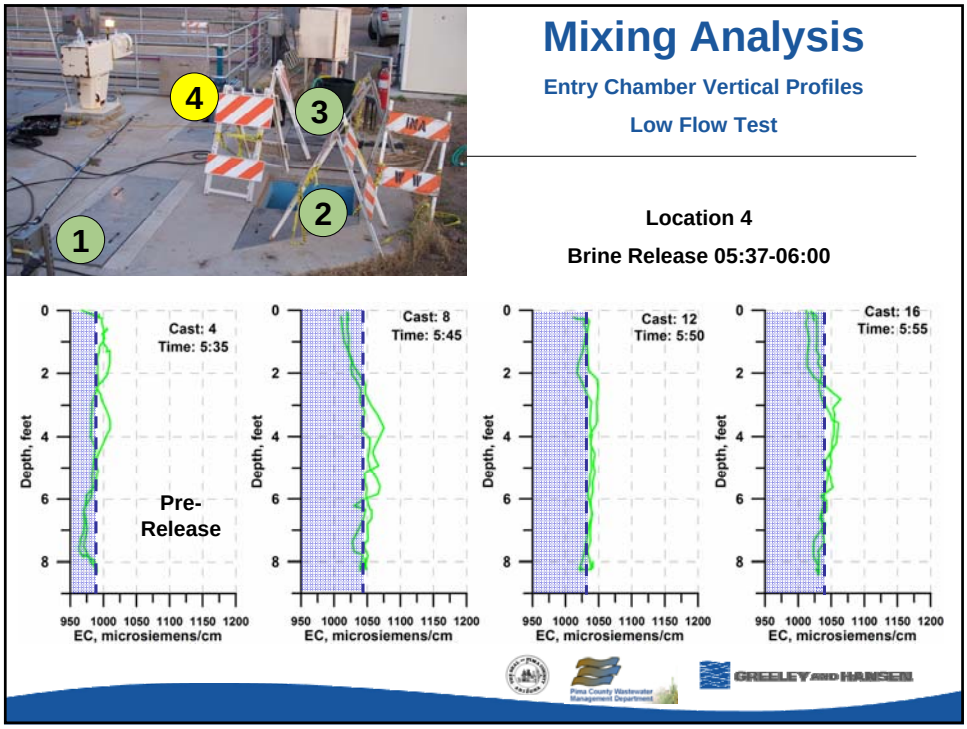
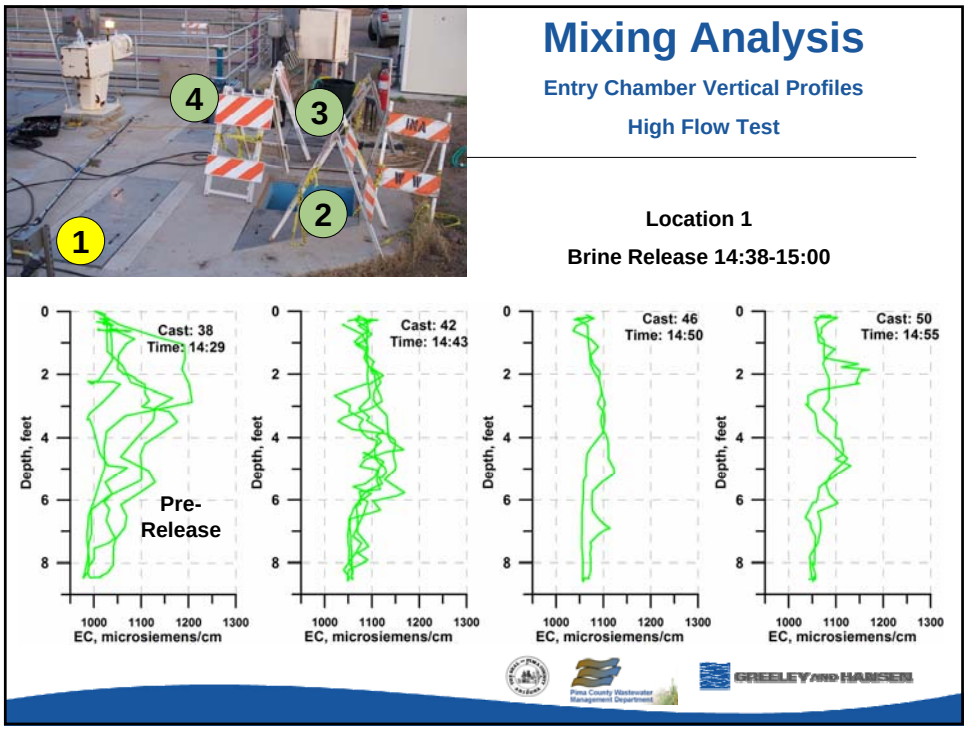
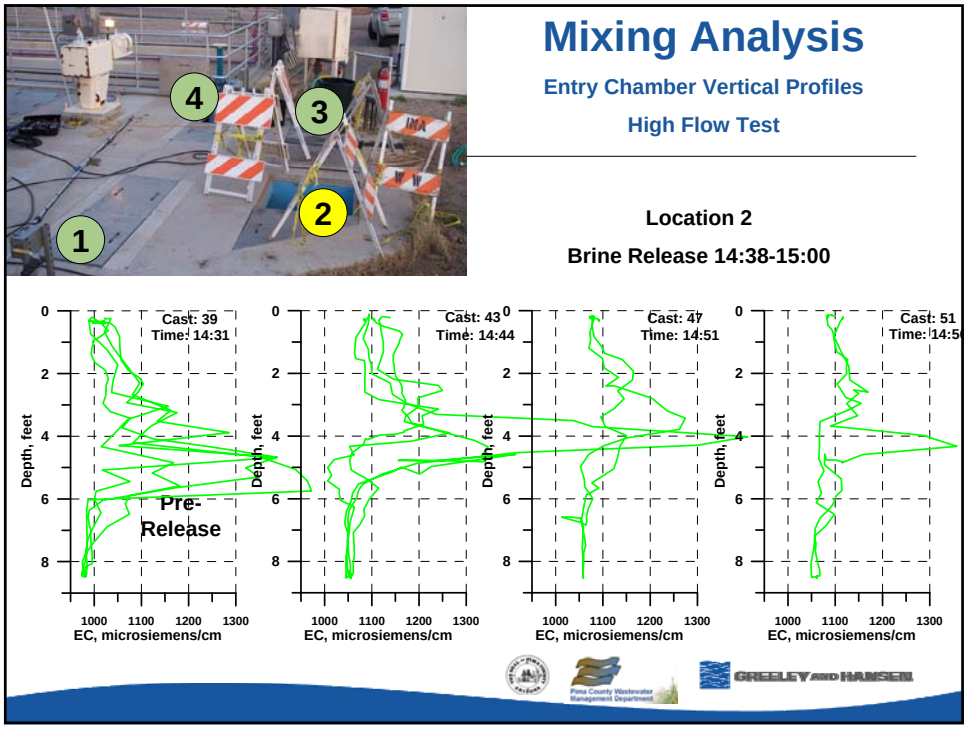
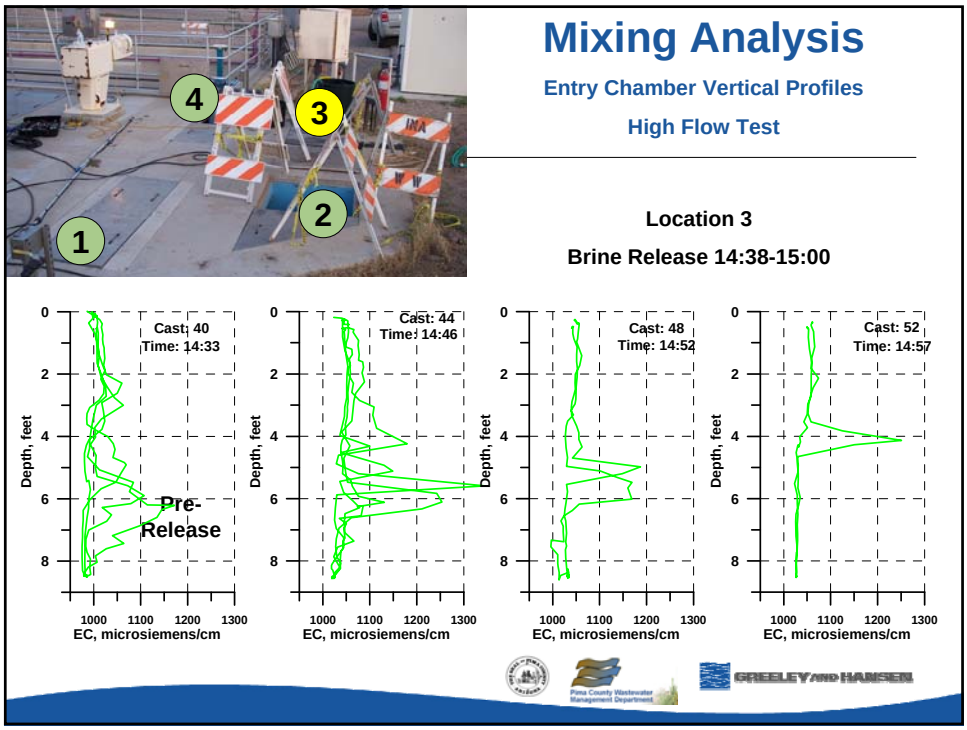

Mixing Analysis
Entry Chamber Vertical Profiles
Low Flow Test
Location 3
Brine Release 05:37-06:00
4
3
2
1
Cast: 3
Time: 5:34
Pre-
Release
Cast: 7
Time: 5:44
Mixing not
occurring at
these depths
Cast: 11
Time: 5:49
Cast: 15
Time: 5:54
Depth, feet
EC, microsiemens/cm
GREELEY AND HANSEN


Mixing Analysis
Entry Chamber Vertical Profiles
Low Flow Test
Location 4
Brine Release 05:37-06:00
4
3
2
1
Cast: 4
Time: 5:35
Pre-
Release
Cast: 8
Time: 5:45
Cast: 12
Time: 5:50
Cast: 16
Time: 5:55
Depth, feet
EC, microsiemens/cm
GREELEY AND HANSEN


Mixing Analysis
Entry Chamber Vertical Profiles
High Flow Test
Location 1
Brine Release 14:38-15:00
4
3
2
1
Cast: 38
Time: 14:29
Pre-
Release
Cast: 42
Time: 14:43
Cast: 46
Time: 14:50
Cast: 50
Time: 14:55
Depth, feet
EC, microsiemens/cm
GREELEY AND HANSEN


Mixing Analysis
Entry Chamber Vertical Profiles
High Flow Test
Location 2
Brine Release 14:38-15:00
4
3
2
1
Cast: 39
Time: 14:31
Cast: 43
Time: 14:44
Cast: 47
Time: 14:51
Cast: 51
Time: 14:5
Pre-
Release
Depth, feet
EC, microsiemens/cm
0
2
4
6
8
1000
1100
1200
1300
GREELEY AND HANSEN


Mixing Analysis
Entry Chamber Vertical Profiles
High Flow Test
Location 3
Brine Release 14:38-15:00
4
3
2
1
Cast: 40
Time: 14:33
Cast: 44
Time: 14:46
Cast: 48
Time: 14:52
Cast: 52
Time: 14:57
Pre-
Release
Depth, feet
EC, microsiemens/cm
0
2
4
6
8
1000
1100
1200
1300
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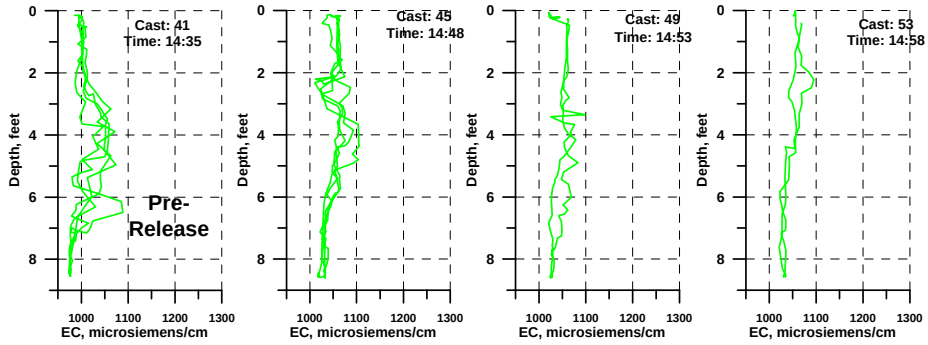
Mixing Analysis

Entry Chamber Vertical Profiles

High Flow Test

Location 4

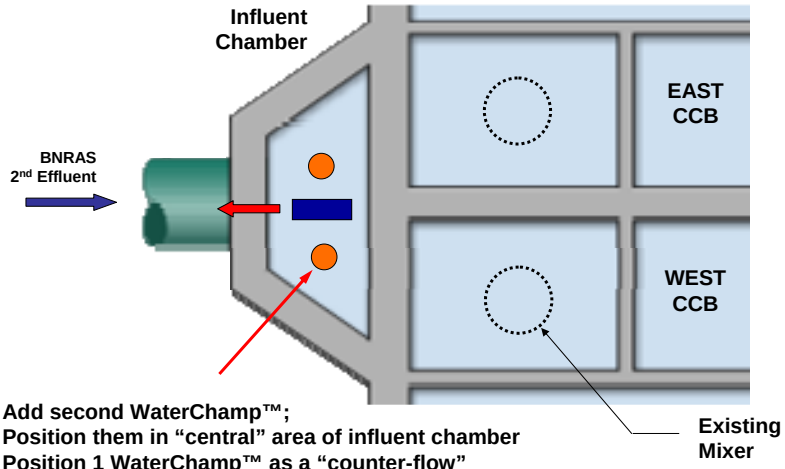
Brine Release 14:38-15:00



Conclusion from Mixing Study

- Mixing in the East and West chambers are similar in characteristic
- Mixing during low flow conditions is inadequate
- Mixing during high flow conditions is reasonable
- Vertical mixing in entry chamber is reasonable
- WaterChamp™ appears to be providing mixing but its position in the influent chamber is not ideal
- Modifications to the chamber should be done to reduce mixing time-to-peak and improve vertical mixing efficiency

Possible Modifications to Mixing Chamber



1. Add second WaterChamp™; Position them in "central" area of influent chamber
2. Position 1 WaterChamp™ as a "counter-flow"

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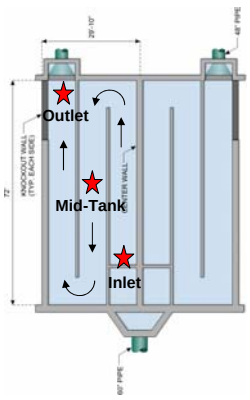
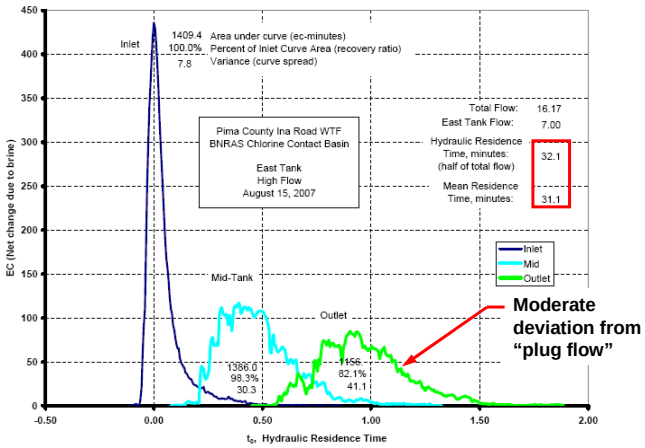
Part 5: Dispersion Analysis – Protocol; Results; Conclusions

David Murray

Dispersion Analysis

BNRAS East CCB – High Flow



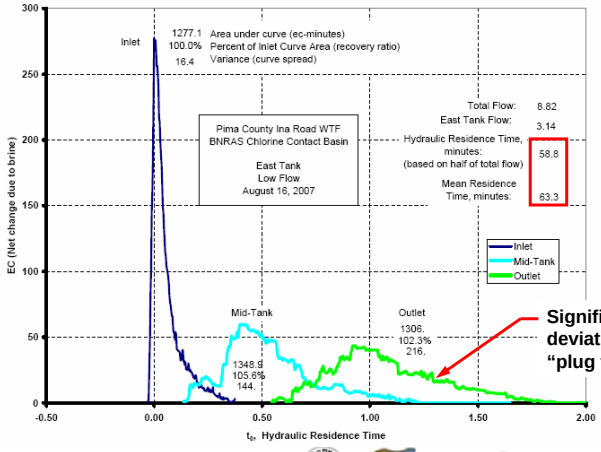


Moderate deviation from "plug flow"

Loss of tracer mass may be attributed to threshold in detection distance from sensor.

Dispersion Analysis

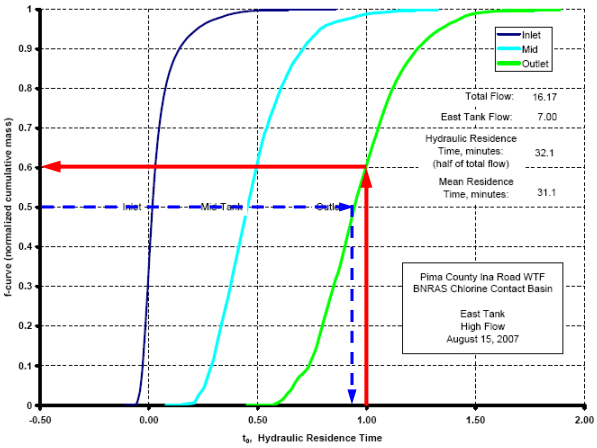
BNRAS East CCB – Low Flow



Significant deviation from "plug flow"

Dispersion Analysis

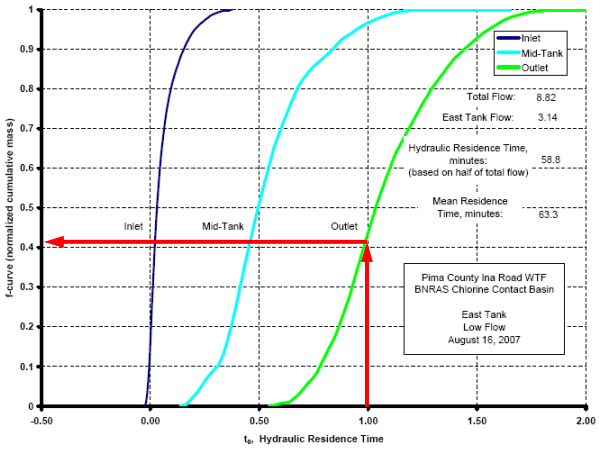
BNRAS East CCB – High Flow



60% of tracer mass passes outlet prior to when theoretical Hydraulic Residence Time occurs for this flow condition.

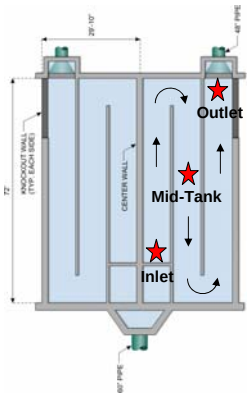
Dispersion Analysis

BNRAS East CCB – Low Flow

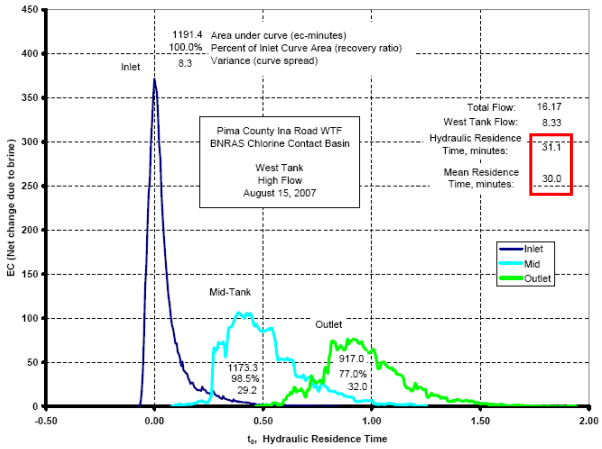


41% of tracer mass passes outlet prior to when theoretical Hydraulic Residence Time occurs for this flow condition.

Dispersion Analysis

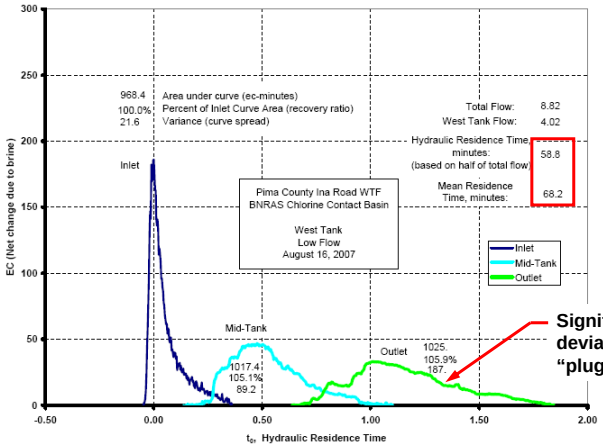


BNRAS West CCB – High Flow



Dispersion Analysis

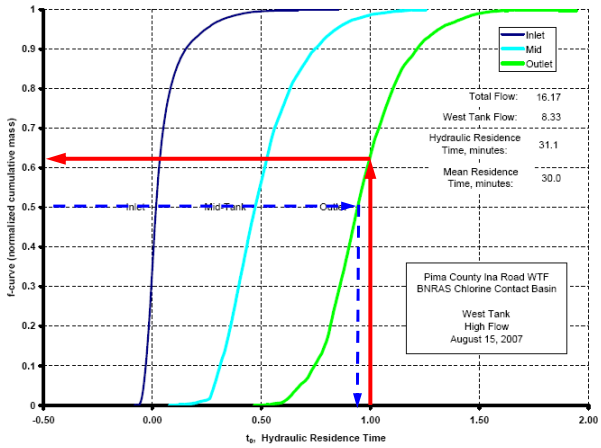
BNRAS West CCB – Low Flow



Significant deviation from "plug flow"

Dispersion Analysis

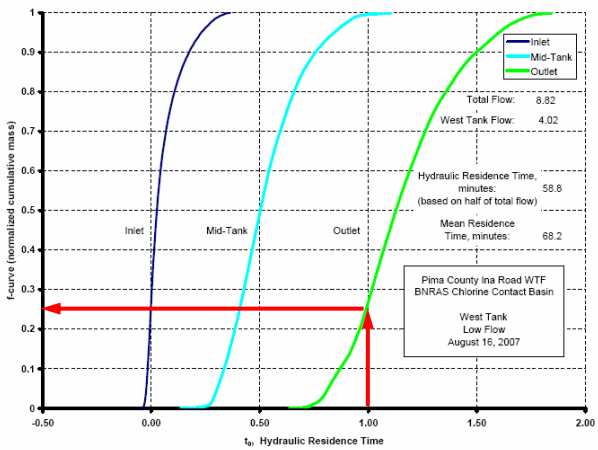
BNRAS West CCB – High Flow



62% of tracer mass passes outlet prior to when theoretical Hydraulic Residence Time occurs for this flow condition.

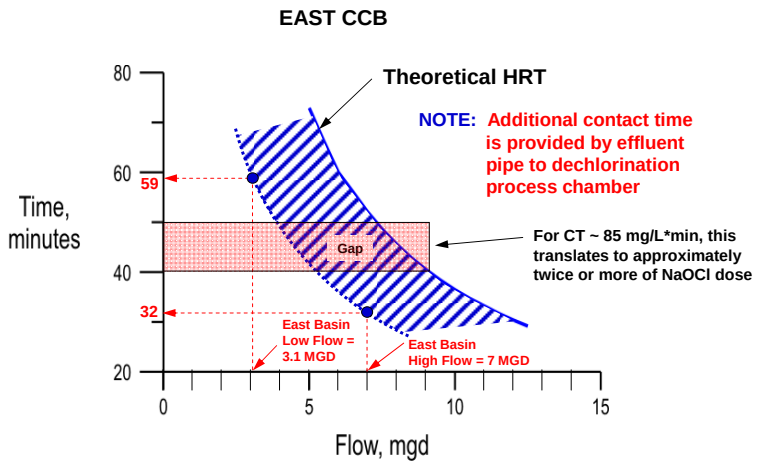
Dispersion Analysis

BNRAS West CCB – Low Flow

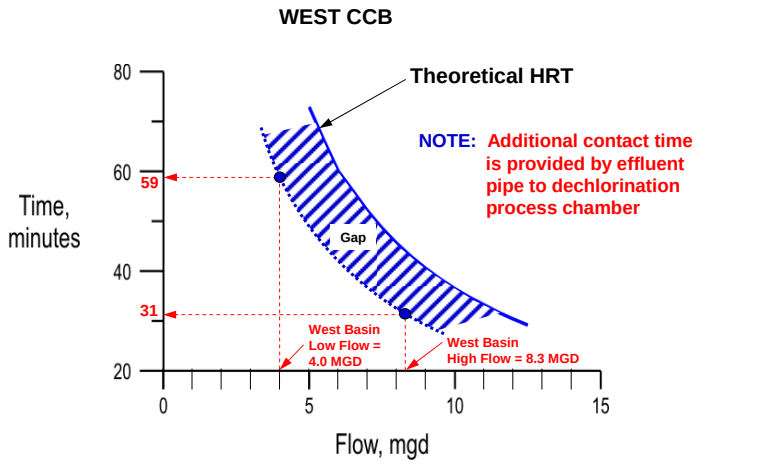


25% of tracer mass passes outlet prior to when theoretical Hydraulic Residence Time occurs for this flow condition.

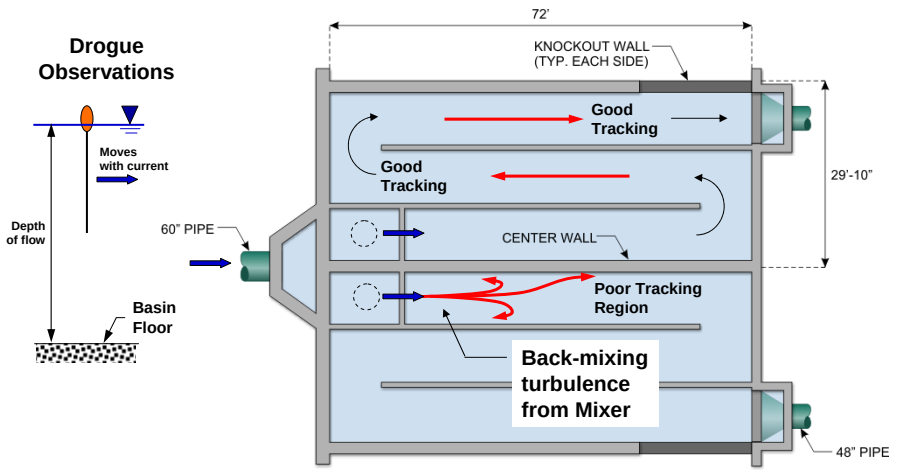
Dispersion Analysis



Dispersion Analysis



Drogue Observations



Conclusions from Dispersion Analysis

- Significant deviations from plug flow conditions exist during low flow periods; moderate deviations during high flow
- Flow regime falls below theoretical HRT under low and high flow conditions → short-circuiting
- Additional contact time is present in effluent pipe conveying flow to dechlorination point
- Severe turbulence caused by flash chamber mixer creates back-mixing in first pass of basin

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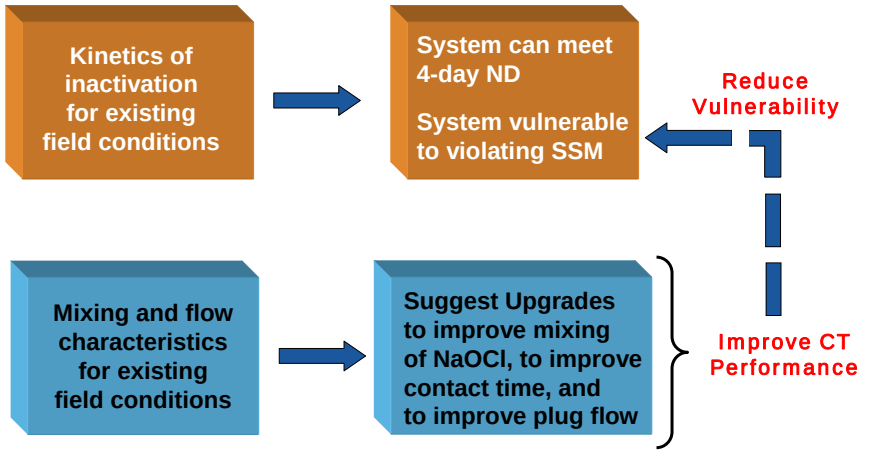
Part 6: Conclusions; Implications; Recommendations

Art Umble

What have we learned?



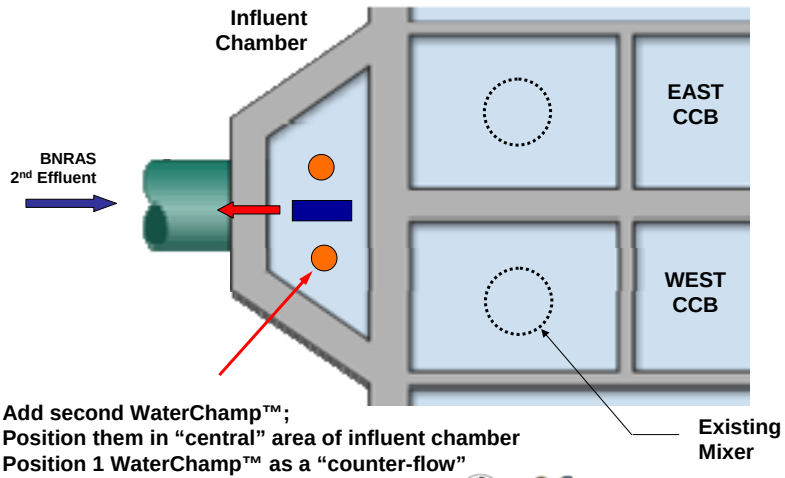
Recommendations

- Improvements to CCB mixing and contact time should result in improved inactivation kinetics
- What are these "improvements?"

Suggested System Modifications / Additions

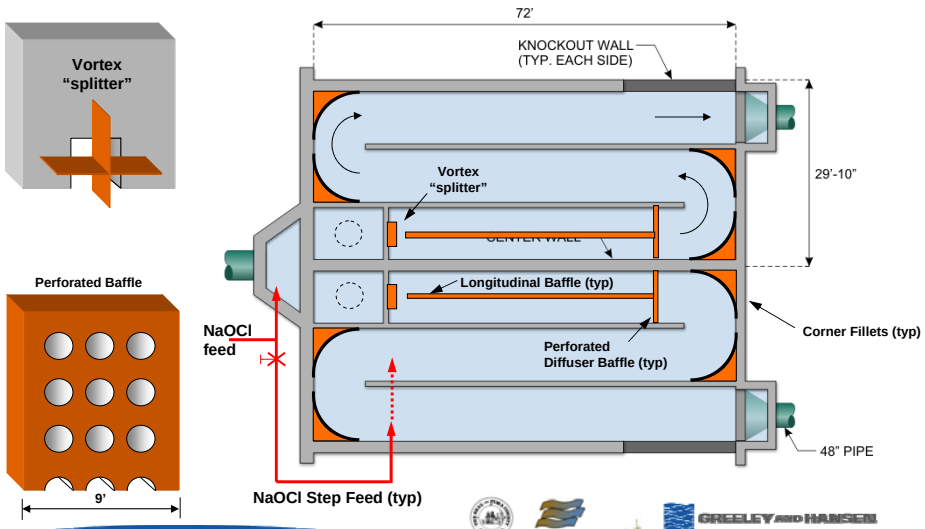
- Mixing chamber: WaterChamp™ Location & Geometry of Chamber
- Chlorine contact basin channels HRT increase
- pH Reduction
- Increases in chlorine dosage
- Increased frequency of basin cleanings
- Coating of basin walls and floor to resist bacterial growth
- Chlorination Step Feed??

Possible Modifications to Mixing Chamber



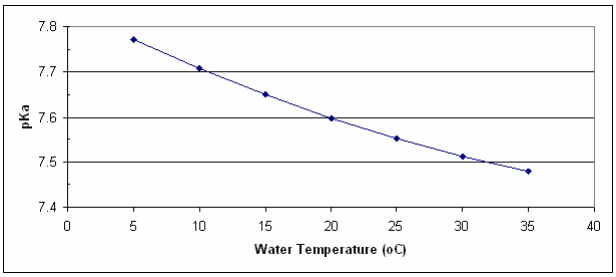
1. Add second WaterChamp™; Position them in "central" area of influent chamber
2. Position 1 WaterChamp™ as a "counter-flow"

Contact Basin Upgrade Concepts



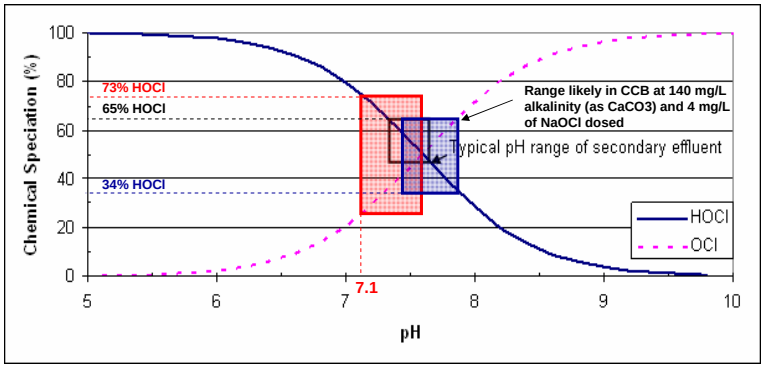
pH Adjustment

- Hypochlorous acid pK_a reduces as temperature increases



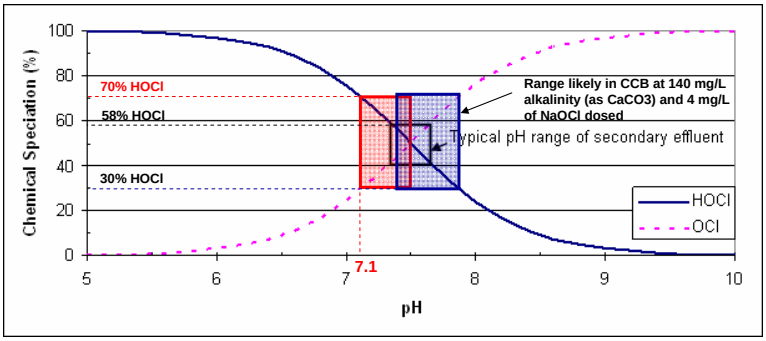
pH Adjustment

- Reduce pH to increase fraction of HOCl in bulk liquid



Reaction Equilibrium at 20ºC

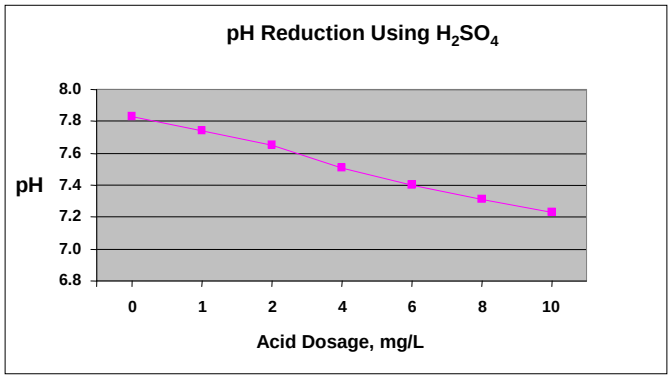
pH Adjustment



Reaction Equilibrium at 32ºC

pH Adjustment

- Add sulfuric acid (inexpensive → $100-$150/ton)



Recommendations

Question: **Can these improvements result in meeting maximum fecal and E.coli permit limits?**

Answer: **For 4-day ND?…Yes (assuming close monitoring)**
For SSMs?…not 100% of the time;
upgrades expected to reduce vulnerability

For vulnerability to violate WET? …out of scope
For vulnerability to production of DPB? …out of scope
For vulnerability to violate Chlorine residual? …out of scope

Strongly recommend that PCWMD laboratory study the WET, DPB and field Chlorine residual responses of the enhanced chlorination process.

Recommendations

- Laboratory "Jar Tests"
  - Establish the chlorine dosage necessary to meet required CT
  - Establish the level of DPBs generated that may impact either WET or APP in the future
- Field Full-Scale Test
  - Verify efficiency of dechlorination to meet residual compliance for chlorine residual.

Recommendations

- Proceed with modifications to the influent chamber, mixing chamber and CCB to improve the reliability of the process
- Consider decommissioning flash mixers
- Proceed with increased frequency of CCB cleaning to remove residual solids
- Proceed with additional bench and full scale testing (PCMWD)
- Confirm enhanced chlorination technology approach with ADEQ

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  jim.doyle@wwm.pima.gov

Appendix G

Enhanced Chlorination / De-Chlorination

Phase I – Literature Review and Assessments

Regional Optimization Master Plan
Enhanced Chlorination Study

Phase 1 – Literature Review and Assessments

Pima County
Wastewater Management Department

July 2007

GREELEY AND HANSEN

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1. Introduction

1.1 Background

The Pima County Wastewater Management District (PCWMD) currently owns, operates and manages a number of wastewater treatment facilities. Over the past year, the PCWMD has been involved in the development of the Regional Optimization Management Plan (ROMP). This plan involves evaluation of the Pima County wastewater treatment facilities with several objectives including:

1) Capacity to accommodate the population growth throughout the region, and

2) Evaluation of the treatment technology necessary to achieve compliance with current and foreseeable future Arizona's environmental water quality standards for discharge of treated effluent to waters of the state or for reuse.

Addressing the disinfection of the plant effluent with respect to the latter objective is the focus of this report. The report examines the efficacy of the existing disinfection technology employed in achieving future compliance. The compliance standards are outlined in the State of Arizona's Administrative Code for environmental regulations. These are referenced as "Best Available, Demonstratable Control Technology" (BADCT) standards for disinfection. In addition, compliance with state's water quality standards for treated effluent chlorine residual and Whole Effluent Toxicity is required by the Arizona Pollutant Discharge Elimination System (AZPDES) permit issued to PCWMD. Additional potential issues of concern include formation of disinfection by-products and enteric virus removals to meet "Class A" water reuse standards.

1.2 PCWMD Objectives

The PCWMD has outlined three fundamental objectives for resolving the position of utilizing chlorination technology for disinfection at their major treatment facilities. These are:

- Meet the BADCT standards
- Meet a "Class A+" effluent quality discharge
- Minimize the necessity for an estimated $70 million expenditure for a filtration and ultraviolet radiation technology approach for disinfection

The set of studies described herein is focused on evaluating chlorination as a technology system for disinfection capable of meeting the objectives above reliably and consistently.

1.3 Study Description

The PCWMD desires to develop its position on meeting the BADCT standards and permit compliance requirements based primarily on evidence presented in three study documents:

1) Literature review on chlorination as a disinfection technology for achieving BADCT standards and AZPDES permit limits

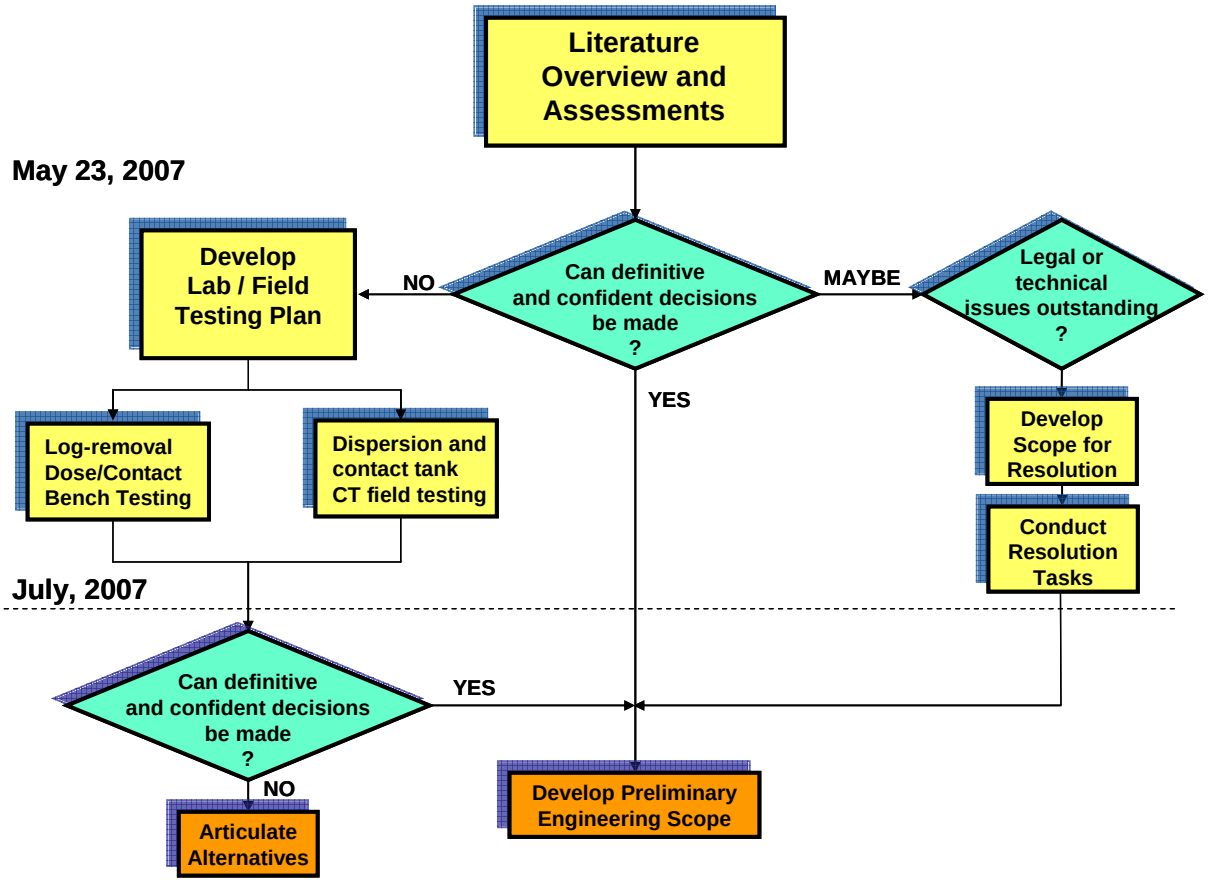
2) Analysis of data collected from laboratory and field studies to confirm and predict the technology performance; and

3) A basis of design, based on findings of research studies and design standards for improvements to existing chlorination facilities.

This report focuses on the results from the literature review. It also includes results of assessments of the existing conditions of the Roger Road Wastewater Treatment Plant (WWTP) and Ina Road Water Pollutin Control Facility (WPCF) disinfection facilities. The emphasis of the assessments is on the Ina Road WPCF since the ROMP calls for eventual replacement of the Roger Road facility.

The literature review and the existing condition assessments provide preliminary information toward the ultimate decisions regarding use of chlorination technology for disinfection. This information can be illustrated in a "decision-tree" process diagram, illustrated in **Figure 1-1,** and briefly described in **Section 1.3.1**.

Figure 1-1



1.3.1 Decision Process

With the information gathered from the literature and condition assessments, the PCWMD can decide if there is sufficient evidence to confidently pursue a chlorination system as the disinfection technology. If the decision is definitive, then the PCWMD would move directly to the conceptual design effort. However, if this determination cannot be definitively made, then additional laboratory and field studies are warranted. These studies would be designed to collect site-specific data related to the inactivation and destruction of potentially pathogenic microbes using the existing chlorination systems, or recommended enhancements to these existing systems. The PCWMD then has a second opportunity to decide if the additional gathered research data is sufficient to move forward with conceptual design. This report presents the findings from the literature review and the field assessments to allow the PCWMD to address the first decision point.

It is hereby noted that all discussion included in this report with respect to disinfection system performance is based on the context of the disinfection facilities at the Ina Road WPCF, with specific emphasis on the disinfection process as part of the existing Biological Nutrient Removal Activated Sludge (BNRAS) process train, otherwise known as the "East Plant" at Ina Road WPCF.

2. Literature Overview

2.1 Organization of Discussion

Results of the literature search and review are summarized in five categories:

- Discussion of the framework of the Arizona BADCT standards in the context of other states with similar regulatory mechanisms, namely Florida and California
- Overview of the "survey of practice" for disinfection in municipal wastewater treatment with respect to treatment train process
- Discussion of the current and future issues surrounding enhanced chlorination technology
- Discussion of the implications of the PCWMD's historical disinfection data from existing chlorination practices
- Proposed additional studies

2.2 Standards and Regulations

2.2.1 Arizona

Title 18 of the Arizona environmental regulations details the rules associated with the BADCT, the Aquifer Protection Program (APP), the national pollution discharge elimination system (NPDES) permitting process, water reclamation for a Class B+ Effluent quality. The basic compliance criteria for these rules as applied to disinfection technology are:

- Fecal coliform and E. coli limits:
  - Non-detect in 4 out of 7 samples per week
  - Single sample: < 23 fecal coliform/100 mL, or < 15 E. coli/100 mL
- Total Nitrogen: < 10 mg/L
- Disinfection by-products:[1] 0.1 mg/L total trihlomethanes (TTHMs) (with 0.08 mg/L as an "alert" level)
- Whole Effluent Toxicity
- Chlorine Residual:[2] < 8 µg/L on a monthly average; < 11 µg/L as a daily maximum

In terms of discharge permits, if a "Class A or A+" discharge quality is desired, monitoring of the effluent for viruses is required, along with associated limits.

2.2.2 Florida

In the State of Florida, "Chapter 62" has a similar set of regulations present with respect to discharge to surface water bodies and for water reclamation (i.e., discharge to a potable water supply). In general, Florida's criteria for disinfection technology are stringent and described in **Table 2-1**.

Table 2-1

Chlorine Contact Tank Influent (fecal coliform / 100 mL)	Required CT (mg/L•min)	Logs of Removal and (%)
≤1,000	At least 25	3 (99.9)
>1,000 – 10,000	At least 40	4 (99.99)
>10,000	At least 120	>4 (>99.99)

In addition, the Florida regulations limit Total Suspended Solids (TSS) in the chlorine contact basin influent to be less than 5 mg/L on a 30-day average. Similar to the Arizona standard on disinfection efficacy, the Florida standard requires that non-detect of fecal coliform be achieved in 75 percent of the samples in a 30-day period, and that each single sample must be less than 25 fecal coliform/100 mL.

A discharge permit in the State of Florida does include limits on specific microbes, i.e., Cryptosporidium and Giardia, when considering the reuse of water or when the discharge is to a drinking water source.

2.2.3 California

In the State of California, the concomitant regulations are found in Title 22, also known as the "Purple Book." California's criteria are based on Total Coliform and enteric viruses (e.g., poliovirus, hepatitis A, human rotavirus, etc.). This set of criteria imposes specific conditions on the reuse of treated water.

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[1] Cyanide will be regulated as a disinfection by-product because of its potential formation from chlorine-based reaction chemistry.
[2] NPDES permit requirement

The treatment goal under this standard for recycled water is a limit of <2.2 total coliform/100 mL for a disinfected secondary effluent, based on a 7-day median. Only one sample in a 30-day period can exceed 23 TC/100 mL, and a maximum for that sample of < 240 TC/100 mL. The reuse of this water is limited to surface irrigation of food crops where the edible portion is produced above ground and is not in direct contact with the recycled water.

For recycled water from tertiary treatment, the California regulations are stringent. In addition to meeting the < 2.2 TC/100 mL (same conditions as the treated secondary effluent), the regulations require the tertiary effluent to be filtered and have a contact time (CT) of 450 mg/L•min along with a modal contact time > 90 minutes under peak, dry weather design flow conditions. This technology must demonstrate at least 5 logs of removal for Ms2 or poliovirus. This level of treatment allows the water to be used for irrigation of edible root crops where the recycled water can be in direct contact with the edible portions. Additionally, these waters can be used for irrigating parks, playgrounds, residential landscapes, golf courses, and are applicable to groundwater recharge for reuse.

Discharge permits in California require monitoring for viruses when discharge is utilized for reuse. However, if the technologies employed achieve greater than 5 log removals, then no monitoring is required. The critical issue here is the definition of the "technology," which is set by the State's Department of Health and Safety rather than the Department of Environmental Quality.

2.2.4 Operational Issues

A set of phone interviews were conducted with operators of some of the Bardenpho facilities (comparable to the future PCWMD facilities) to determine if there were operational issues over and above compliance issues that favor one disinfection technology approach over another. In each case, no specific problems or violations were reported after a completed start-up procedure. However, several reported that the time for bringing the process under full operational control required 6 months to a year. Also, in a number of cases, operators reported experiencing problems with scum and floatables in the contact facilities. Finally, most operators stated that in order to meet a ≥ 4 day fecal coliform non-detect criteria, filtration was recommended.

2.2.5 Additional Current Issues

There appears to be evidence that consistently and reliably meeting maximum limits for fecal coliform and E.coli criteria (such as those outlined for PCWMD) is a technological and operational challenge. This also does not seem dependent on whether or not filters are used with either a chlorine or UV-based disinfection system approach.

When considering the process of enhanced chlorination, in which higher chlorine doses along with longer contact times, additional compliance requirements may arise. These relate mostly to complying with WET test criteria for chlorine residual, ammonia, and sulfite (resulting from dechlorination systems). With the increased chlorine dosages, there is the higher probability of increases in chlorinated disinfection by-products (THMs and haloacetic acid (HAA5s)). There is also the possibility that cyanide would be included in this disinfection by-products (DBP) group of regulated compounds.

2.2.6 Potential Future Issues

The regulatory horizon is not clear as to what new regulations on treated effluents will be issued over the next few years. However, in Arizona, it is possible that enteric viruses will be added to the regulation for discharge waters slated for greater than Class A quality reuse as potable aquifer recharge. In Florida, it seems possible that enterovirus will be added to the regulations for water recycling programs and a lower THM/HAA5 limit. These lower limits on DBPs may be actually lower than those imposed for drinking water standards. In California, for groundwater recharge recycling programs, the inclusion of N-methyl-D-aspartic acid (NDMA) is possible, as well as new, much lower limits on THMs/HAA5.

2.3 Survey of Practice

2.3.1 Disinfection

In the United States, chlorination technologies have dominated disinfection practices in the municipal wastewater treatment industry for decades. However, that dominance has been declining in recent years, primarily due to changes in environmental regulatory policy and shifts in public's perception for what is safe practice in utilizing hazardous chemicals. Thus, there is has been an increase in the application of ultraviolet (UV) radiation as a disinfection technology. Figure 2.1 illustrates the breakdown of disinfection practices across the US (based on 2006 data).

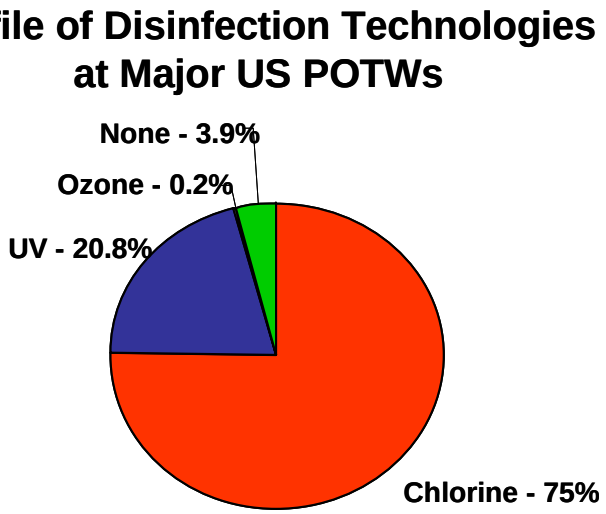
When considering the comparison of the PCWMD facilities at Ina Road WPCF and Roger Road WWTP to comparable facilities across the US in terms of disinfection practice, in general UV makes up less than 18 percent of the technologies employed. This is depicted in **Table 2-2.**

Table 2-2

Treatment Plant	Flow Range (mgd)	No. of POTWs	No. of Plants Utilizing UV
Roger Road	22 - 42	149	25
Ina Road	40 - 60	67	10
Combined	72 - 92	18	1

It is interesting that though UV appears to be gaining favor in the US, there remains an inverse correlation between size of plant and utilization of UV as the disinfection technology. This may be related to higher capital and O&M costs generally associated with larger installations.

Figure 2-1



2.3.2 Treatment Process

Currently, the Ina Road BNRAS facility utilizes a nutrient removal system similar to the future Bardenpho treatment process. A Bardenpho process designed to maximize reduction of total nitrogen from the wastewater stream typically consists of a minimum of a treatment train of 4-stages in series. In the United States today, there are 45 major POTWs (design flow rates of 1 - 24 MGD) that utilize the Bardenpho process. The State of Florida dominates in the number of Bardenpho plants with 22, followed by Maryland with 8. Nine states, which include Arizona, have one or two such plants. (Interestingly, of these 45 major plants, 12 employ UV as the disinfection technology.)

2.3.2.1 Relationship of Process and Disinfection Technology to Microbial Violations

The Bardenpho process is generally considered capable of producing a high quality secondary effluent. This high quality should improve the efficiency of the downstream disinfection process, and thus translate to fewer violations of the permit for microbial criteria. A summary of these findings is given in Table 2-3. From this data, of the 17 Bardenpho plants with microbial performance violations, 11 were plants that utilize chlorination with filtration. However, only 3 Bardenpho plants that practice only chlorination experienced violations. The type of violation is also important to note. Of the violations listed, the most common was violation of the single sample maximum. Only one Bardenpho plant showed a violation of a periodic average. It should be noted that conclusions cannot be drawn from this information with respect to relationship between disinfection technology and violation. It is not known in any of the cases listed the cause of the violation. However, what the information does show is that merely adding filtration to either UV or chlorination disinfection technology is not a fail-proof guarantee against violation.

Table 2-3

Disinfection Technology	Flow Range (mgd)	No. of POTWs	No. of POTWs with Microbial Violations of Maximum*	No. of POTWs with Microbial Violations of Periodic Average*
UV	17	1	1 (6)	0
Filtration + UV	12, 15	2	1 (2)	0
Chlorine	4 - 22	3	1 (1)	0
Filtration + Chlorine	6 - 24	11	8 (25)	1 (1)

( ) = total number of violations for category

2.3.2.2 Relationship of Process and Disinfection Technology to WET Violations

Because the Whole Effluent Toxicity (WET) test is an element of compliance, the violation of a WET test from these same 17 Bardenpho plants was examined. The results are shown in Table 2-4. Similar to the microbial violations, the violations of WET were found to be highest at the Bardenpho plants that use filtration with chlorination. This could be argued as significant since these occurred at 10 different plants. On the other hand, though the plants having only chlorine as their disinfection technology made up the majority of other WET violations (6 water flea violations and 4 minnow violations), these each occurred at only one facility. Again, the information in **Table 2-4** indicates that merely adding filtration ahead of either UV or chlorination disinfection technology is not a fail-proof guarantee against a WET violation.

Table 2-4

Disinfection Technology	Flow Range (mgd)	No. of POTWs	No. of POTWs with WET Violations of Water Flea*	No. of POTWs with WET Violations of Minnow*
UV	17	1	1	0
Filtration + UV	12, 15	2	1	0
Chlorine	4 - 22	3	1 (6)	1 (4)
Filtration + Chlorine	6 - 24	11	10 (23)	5 (25)

( ) = total number of violations for category

2.3.2.3 Relationship of Process and Disinfection Technology to THM Violations

There are few plants in the US that currently operate under permits with limits for total trihalomethanes (disinfection by-products). Of the seven facilities found in this study to have such limits, each is configured with filtration followed by chlorine for disinfection. Thirty-seven disinfection by-product violations (TTHM and dichlorobromomethane, primarily) have been reported from these seven facilities. Perhaps more significantly, the violations for 6 out of the 7 facilities correlated closely with violations of maximum concentration limits and with WET operational issues

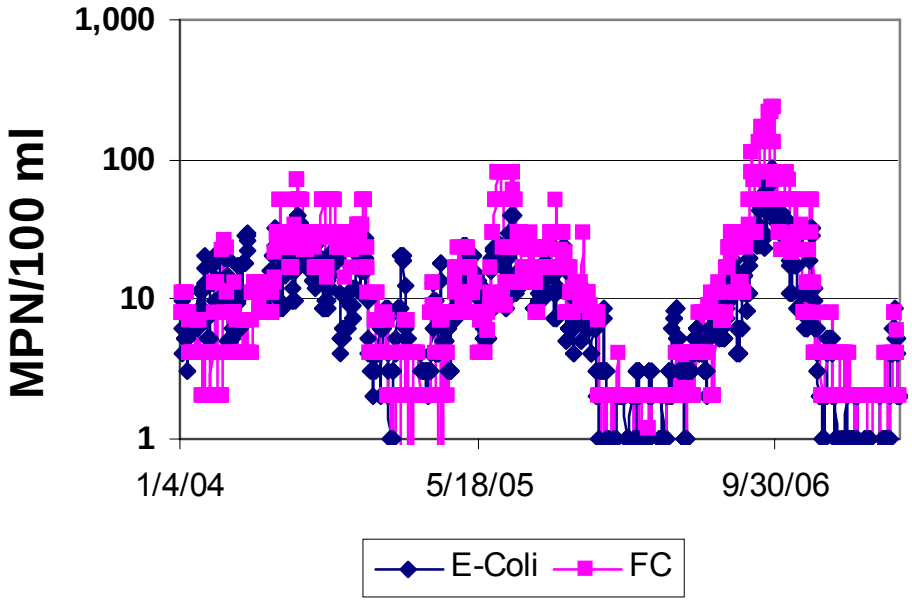
2.4 Implications from Preliminary Analysis of PCWMD Performance Data

As the PCWMD continues forward with consideration of utilizing an enhanced chlorination technology approach for its wastewater treatment facilities, it is important to conduct a cursory review of the available disinfection performance data from current operations in the context of the literature findings. From this review, and using a statistical approach, inferences can be made as to whether or not the enhanced chlorination approach could be successfully applied (meaning reliable and consistent in meeting standards) at the PCWMD facilities.

This review focuses on Ina Road WPCF performance data from the period of January 2004 through April 2007. The first step in this review is to develop a frequency distribution of the available data. This analysis involves tabulating the MPN/100 mL for fecal coliform and E.coli into categories of percent of occurrence. These are then plotted on log-scale as a function of percent of occurrence.

Figure 2.2 is a plot of the disinfected effluent data provided by PCWMD. The general trend of this data follows seasonal patterns, with higher values in the summer months, corresponding to higher temperatures and wet weather conditions.

Figure 2-2

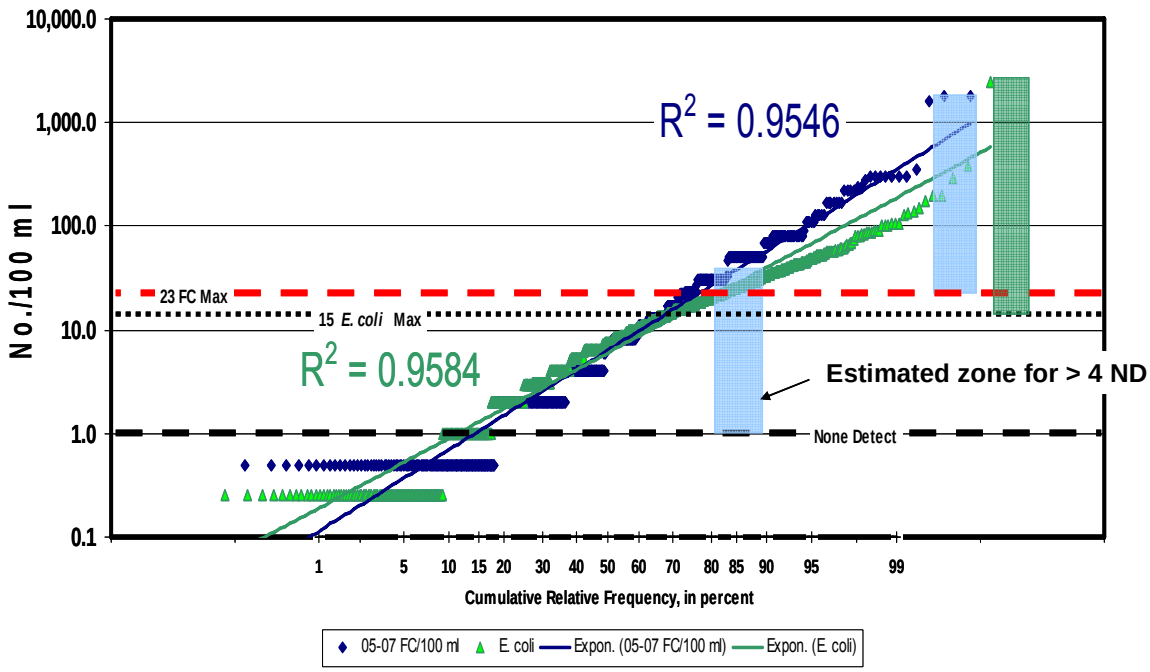


This data for both fecal coliform and E.coli were found to follow a log-normal distribution. This data was then plotted into a cumulative frequency distribution diagram, illustrated in **Figure 2-3**. Implications for PCWMD from this frequency distribution are important to recognize. Several most probable number (MPN) levels are noteworthy. First, is the threshold of 1 MPN. This threshold essentially represent the non-detect level. So, in order to reliably meet the 4-day non-detect requirement, the majority of the fecal coliform data (probably at least 75% to 85%) would need to plot below this line. Of the data analyzed, approximately 20% of the fecal coliform samples historically fall at or below this level.

Secondly, approximately 70% of the E.coli data falls below the threshold of the maximum limit of 15 MPN/100 mL and approximately 75% of the fecal coliform data falls below the threshold of the maximum limit 23 MPN/100 mL. Any fecal coliform and E.coli value plotted above these respective thresholds represent potential violations of a maximum limit under the BADCT standard. Here again, in order to sustain reliable, fail-proof compliance, 100% of the fecal coliform and E.coli data would need to plot below the 23 MPN and 15 MPN lines, respectively.

Results of this plot point to the number of logs of removal that must be reached in order to have the cumulative relative frequency consistently fall below the thresholds. For the data analyzed, an additional 1.5-log removal of would be necessary to consistently achieve the 4-day fecal coliform non-detect standard. To reliably achieve the < 23 MPN maximum limit, an estimated additional 2 logs of removal would be necessary. For E.coli, approximately 2.2 logs of additional removal performance would be necessary to meet the < 15 MPN maximum limit.

Figure 2-3



Close observation of the results of this frequency distribution analysis is that only a few outlier points of fecal and E.coli plot above 1000 MPN. These outlier events make up less than 0.5% of the data. If these points are removed from the analysis, the increase in log-removal necessary to meet the maximum limit requirements is less, i.e., approximately, 1.2 and 1.4 for fecal coliform and E.coli, respectively. This raises several important questions for the PCWMD to address.

1. What level of risk of maximum limit violations (of the sort that make up these few high value outliers) should the PCWMD be willing to accept?
2. Is there a point in the cost/benefit analysis, beyond which, the cost to provide facilities to ensure consistent and reliable compliance that includes the outlier events returns no additional benefit to the PCWMD?
3. Should the PCWMD build enough facilities as much as necessary to ensure maximum probable compliance?

It is important to note that the data presented in Figures 2-2 and 2-3 represent microbial samples taken from the blended effluent from the BNRAS and the High-Purity Oxygen (west) plant, and therefore the exact contributing source is unknown. But literature does indicate that upstream process does play a role

when determining the level of log-removal necessary.[3] Biological nutrient removal systems appear to achieve at least 1-log lower fecal coliform count in the effluent when compared to conventional activated sludge systems. This is outlined in **Table 2-5**. Because the PCWMD employs a biological nutrient removal process, it is likely that the actual log-removal required will be lower than what is shown in **Figure 2-3** since what is presented is a blended effluent condition.

Table 2-5

Secondary Effluent	FC / 100 mL	Estimated Log-Removal to 4-day ND
Activated Sludge	29,300	4.7
Nitrified Activated Sludge	37,000	4.8
Biological Nutrient Removal	3,600	3.8

2.5 Studies to Establish Kinetics of Microbial Inactivation on PCWMD Effluent

Results of the data analysis discussed Section 2.4 suggest that a decision to accept the enhanced chlorination as the appropriate process for PCWMD and to proceed directly to a conceptual basis of design effort for the enhanced chlorination process (first critical decision point in the flow-chart diagram shown in Figure 1-1) would be premature at this juncture. Therefore, the following additional studies are recommended to provide additional information to support an informed decision.

2.5.1 Disinfection Kinetics

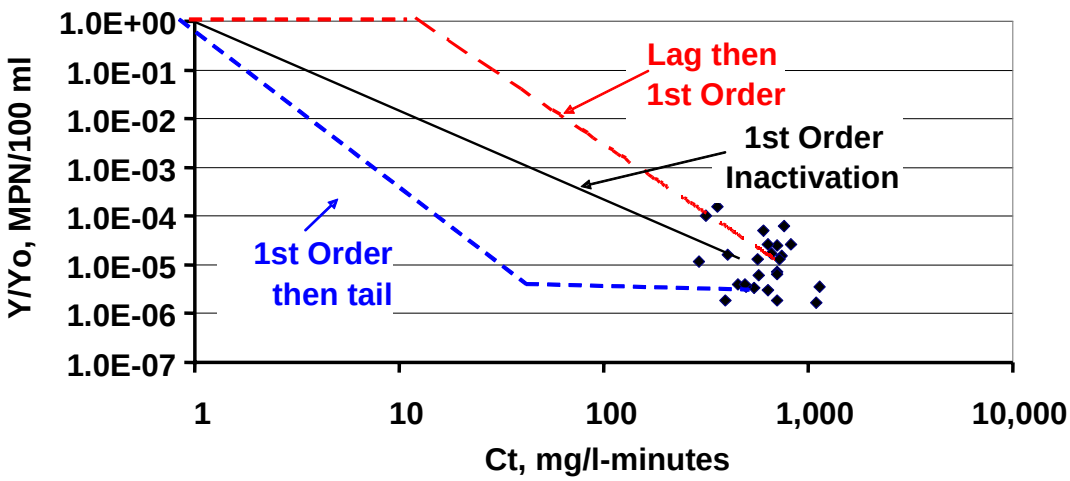
Degree of inactivation of microbes under exposure to an oxidizing (disinfecting) agent depends on both the dose of the agent and time that the organism is held in contact with that agent. Mathematical models exist to describe this relationship and provide valuable insight into the effectiveness of a given disinfectant. A model known as "Crick's Law" is perhaps the most widely used. This maps the relationship between the concentrations of viable organisms present, with respect to an initial concentration, as a function of the time that the organisms are exposed to the disinfectant and the dose applied to create the exposure. A true "1st Order" response plots as a straight line on a log-log plot. However, such models do not take into account the variability in characteristics commonly found in wastewater effluents. The more common response for wastewater effluent can be illustrated in Figure 2-4 (hypothetical data shown).

Effective disinfection would be representative of a 1st Order inactivation relationship. With respect to the PCWMD facilities, if the disinfection kinetics show a true 1st Order relationship, perhaps effluent filters would not be necessary. However, as the figure illustrates, there are often departures from this relationship, represented by the "lag" or the "tail" responses. In the case of the "lag" followed by a relative 1st Order response, this represents a condition where particulate constituents in the suspending liquid react initially with the disinfectant, and essentially render the disinfectant inactive for a period of

[3] Rose, J., et al., WERF 2004

time. The implication of this for the PCWMD would be an adjustment to the disinfectant dose being applied. In the opposite, or "tail" case, this is reflective more of the presence of large particles in the water column shielding the organisms from the disinfectant. The slope of this "tail" is reflective of the size distribution of particulates that are present. With respect to the PCWMD facilities, a kinetic response with the "tail" could be an indicator that effluent filters would be a necessity.

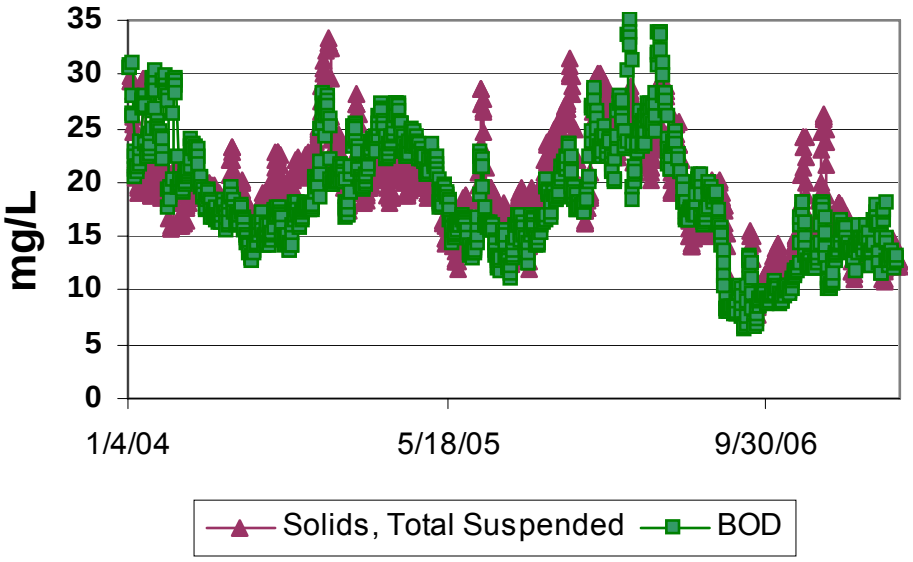
Figure 2-4



It is not uncommon for the kinetics to show a combined response between these two phenomena. **Figure 2-5** shows the effluent TSS and biochemical oxygen demand (BOD) data from the Ina Road WPCF. This data illustrates that TSS does indeed fluctuate with season, presumably concomitant with seasonal flow variation and therefore may influence disinfection kinetics. (Again, it is recognized here that the effluent TSS and BOD values reflect the combined BNRAS and HPO plant effluents).

Results of the kinetics analysis provides insight into the design of a chlorine disinfection system, both in terms of the initial mixing of the chlorine with the bulk liquid, and with the contact time required for reaching the desired inactivation levels.

Figure 2-5



2.5.1.1 Recommendation: Disinfection Kinetics Study

It is recommended that the PCWMD conduct a bacteriological inactivation study to establish the kinetics associated with the PCWMD effluent. It is recommended that the BNRAS secondary effluent[4] at the Ina Road WPCF be used as the source for the kinetics evaluation. Pragmatically, this test establishes the overall contact time, "T" in the "CT" product necessary to meet the BADCT.

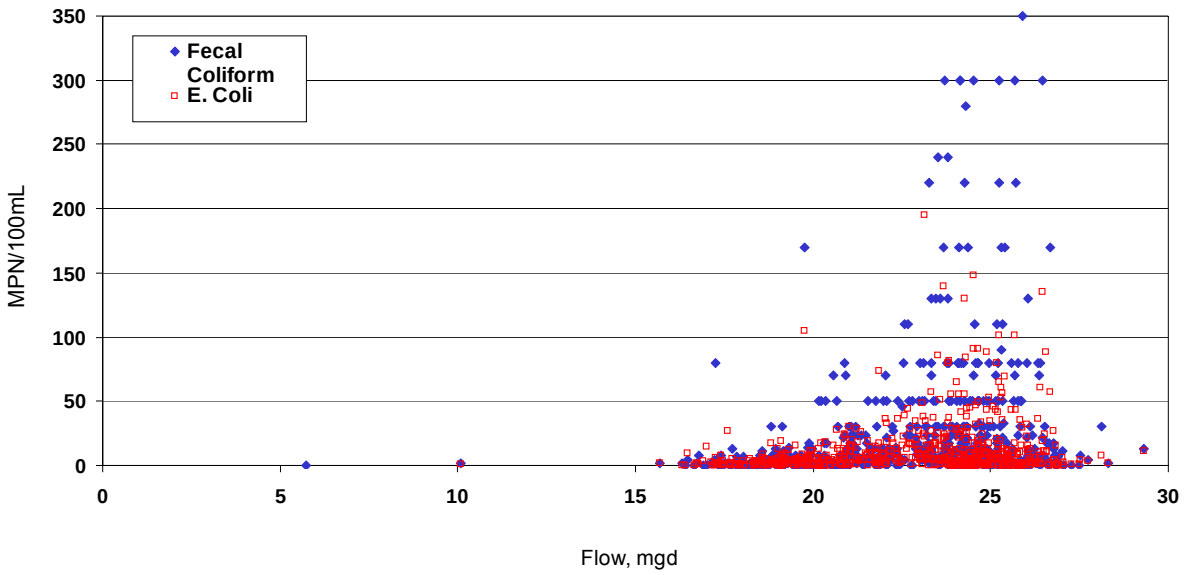
This study would pull samples from the fully mixed region of the chlorine mixing chamber immediately upstream of the chlorine contact basin and use "bench holding times" to simulate the chlorine contact time. The test should be conducted for both fecal coliform and E.coli. It is recommended that the test be repeated through at least seven independent sampling events, with multiple replicates of fecal and E.coli runs for each set. This ensures reasonable integrity for the statistical analyses. To set the baseline concentrations (C_o) of the target organisms, an unchlorinated, unfiltered sample must be drawn upstream of the mixing chamber and chlorine injection point. To examine the kinetic effects of increased TSS that may be present, it is recommended that this baseline concentration sample be drawn from the secondary clarifier having the poorest performance. As an alternative, a TSS spike can be added to the baseline sample to simulate high solids conditions. To enhance the analysis, it is further recommended that methods be used that can detect fecal coliform to levels less than 0.02 MPN/100 mL.

[4] The PCWMD master plan calls for the new facilities to be designed and constructed as Bardenpho, but operated as a BNRAS, similar in process configuration to that of the existing "east" plant at Ina Road.

2.5.1.2 Recommendation: Microbial (Fecal Coliform and/or E.coli) Characterization Study

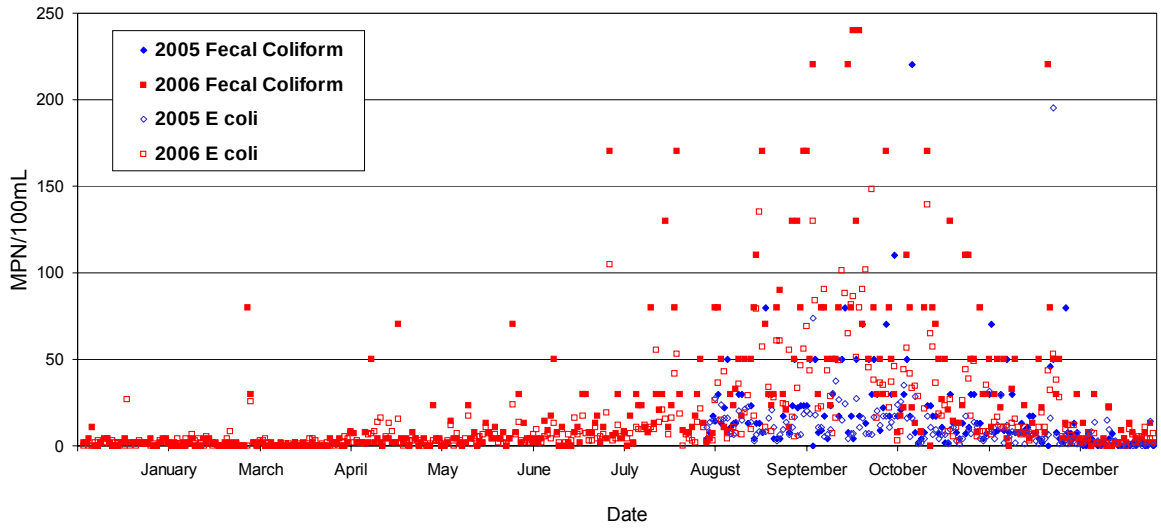
It is clear from the historical data provided by PCWMD that there exists a degree of variability in the effluent concentrations of the target organisms throughout different times of the year. This variability refers to variability in influent flow. Generally, higher TSS is attributed to higher flows. This is evidenced by the data shown in **Figure 2-6,** where a correlation exists between plant flow and microbial counts in the final effluent at the Ina Road facility.

Figure 2-6



The data shown in **Figure 2-7** shows the relationship between microbial counts in the effluent with different times of the year. Though this figure seems to imply that the summer months represent a significant challenge on disinfection performance, this data set is somewhat misleading. During the latter months of the summer of 2006, the new BNRAS facility (east plant) at Ina Road was brought on line. During that time, disruption to normal operation was inevitable resulting in microbial counts higher than normal. However, operators do confirm that summer conditions do pose more stress on the chlorination system than at other times of the year.

Figure 2-7



It is important, then, to examine the disinfection effectiveness in the context of this variability. This study consists of measuring the concentration of the target microbe(s) at a point immediately upstream of the chlorination injection/mixing and immediately upstream of dechlorination. The efficiency of the dosage combined with the contact time results in a total inactivation (i.e., total logs removed). Essentially, this test establishes the necessary residual concentration "C" of the disinfectant, for the "CT" product. This residual is typically measured at the end of the contact "flow path" just prior to dechlorination.

This study will provide the evidence necessary to support or refute meeting the 4-day non-detect BADCT criteria. If it is found that > 6 logs of removal is necessary (particularly under conditions of high flow and high TSS) to ensure the 4-day non-detect can be reliably met, then it is probable that the enhanced chlorination process is not the appropriate disinfection process for this treatment plant. If, on the other hand, it is found that < 4 logs of removal (again, particularly under high flow and solids conditions) is required to sustain a 4-day non-detect compliance, then it is possible that enhanced chlorination may indeed be the right choice, and that filtration may not be necessary. For a removal level somewhere between these two "targets," filtration will likely need to be considered.

Ideally, a collection of between 10 and 30 data points (each collected under a variety of flow and suspended solids conditions) would sufficiently characterize the inactivation response of the target organisms under the chlorination dose and contact times provided by the existing system.

It is recommended that this test be performed on the BNRAS secondary effluent.

2.5.1.3 Availability of Laboratory Facility to Conduct Kinetics Studies

The Ina Road WPCF laboratory facility consists of three divisions: microbiology, nutrients, and organics. In general, analyses are completed within one week of sample and lab reports are available within two weeks. All QA/QC functions are performed by a separate group, and QA/QC of analytical equipment is conducted daily with calibrations conducted monthly.

The challenge for the laboratory in conducting the microbial tests described above is available incubator space. Consequently, it is the laboratory staff's preference to conduct E.coli testing rather than fecal coliform. It is recommended that the PCWMD consider augmenting laboratory services, if necessary, to conduct the above tests. Currently, as demand requires, the laboratory facility does contract analytical services to an outside source (Aquatic Consulting & Testing, Inc., Tucson, AZ).

The Whole Effluent Toxicity (WET) testing was initially performed on-site. But in 1999, the Arizona DEP issued a waiver that reduced the WET test requirements. Since then, this test has been contracted to an outside laboratory (GEI Consultants, Inc., Littleton, CO). However, the new permit requires an increase in the WET test frequency. The PCWMD is therefore considering resumption of on-site WET testing. Depending on the timing of the WET testing, this should be taken into consideration with respect to the resources required for the above described studies.

3. System Assessments

3.1 Existing Disinfection Facilities[5]

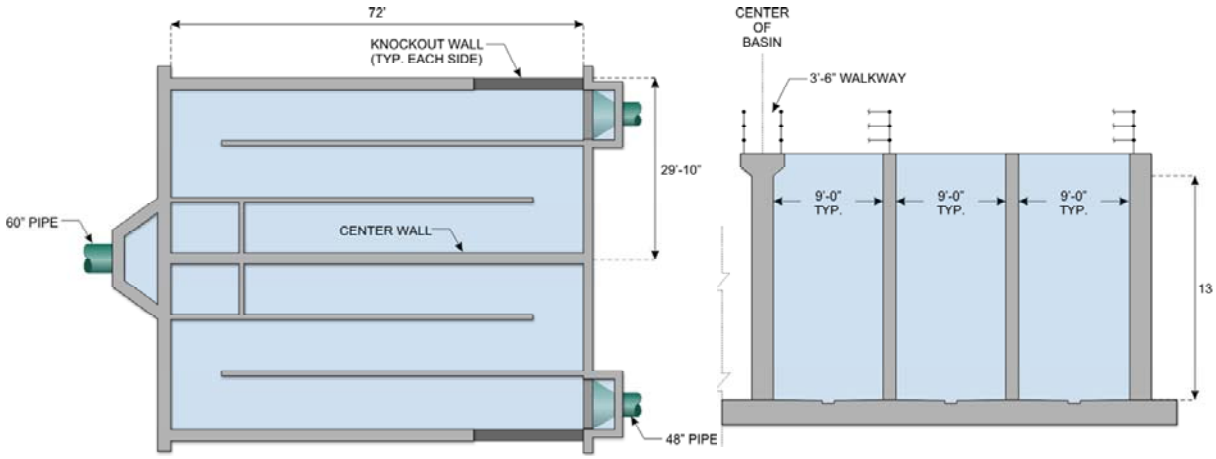
At the Ina Road WPCF, two parallel treatment process trains exist. The "west" plant is a conventional high-purity oxygen (HPO) process rated fro 25 mgd. The "east" plant is a biological nutrient removal activated sludge (BNRAS) process rated at 12.5 mgd. Currently, the BNRAS plant is operated at a constant, steady-state flow (flatlined), while the HPO operates under diurnally fluctuating flowrates. Each treatment train is served by its own hypochlorite disinfection system (including instrumentation and controls). Effluent from each chlorine contact basin is then combined prior to dechlorination and final discharge. Compliance of microbial criteria is monitored downstream of the dechlorination point, just prior to final discharge.

3.1.1 BNRAS Plant Disinfection System

The chlorine-based agent used for disinfection is hypochlorite. The contact basin for the BNRAS plant consist of two parallel, square flash mix chambers (outfitted with both a vertical turbine mixer unit and a Water Champ® for hypochlorite injection), followed by two parallel, serpentine plug flow contact channels. Secondary effluent flow is split evenly between the two parallel configurations. The schematic plan and cross section of this system is shown in **Figure 3-1**.

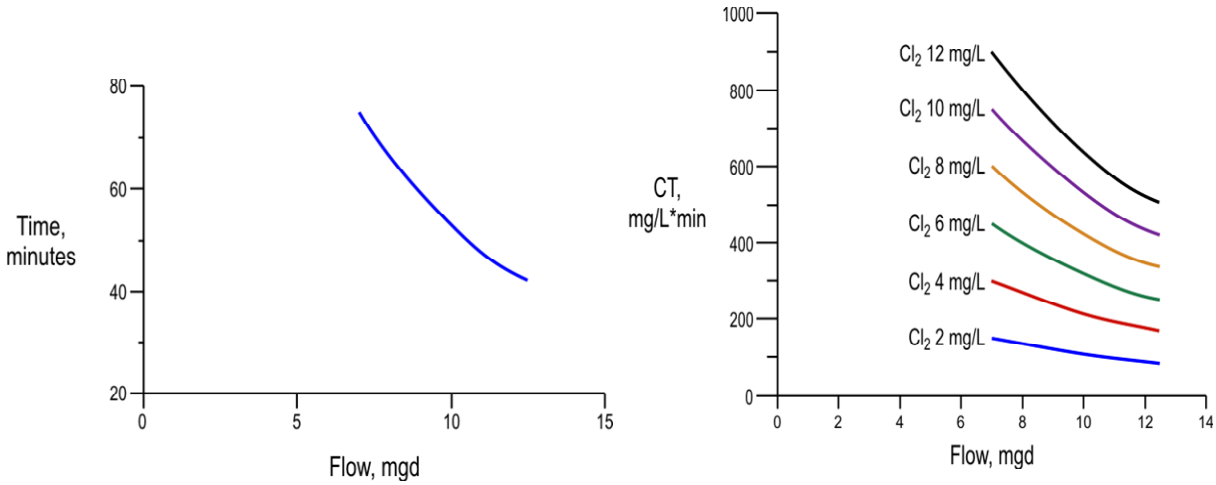
[5] The PCWMD master plan calls for decommissioning the existing Roger Road WWTP and replacing it with a new facility. Therefore, this report does not address disinfection facilities at Roger Road WWTP.

Figure 3-1



Understanding the hydraulic characteristics of the geometry of this basin system is critical to the issue of determining if an enhanced chlorination system is the most appropriate technology to reliably and consistently achieve the BADCT standards. Hydraulic retention time (HRT) as a function of flowrate provides the theoretical basis for establishing CT. This is depicted in the graphs in **Figure 3-2** for the flow ranges typically seen through the BNRAS process.

Figure 3-2



These graphs indicate that for flows ranging from 7 to 12.5 MGD, the theoretical HRT ranges from approximately 75 minutes to 40 minutes, respectively. Approximately 40 and 20 minutes of additional residence time for contact are provided to the 7 mgd and 12.5 mgd flowrates, respectively, to account for the travel time in the 48-inch discharge pipe that conveys the flow from the basin to the dechlorination chamber. **Table 3-1** shows the range of theoretical CT values applicable to this facility under a range of chlorine residuals. The highlighted row represents the typical target of operation practiced currently by the PCWMD for the BNRAS plant.

Table 3-1

Chlorine Residual[a]	BNRAS Flow[b]	HRT_t[c]	CT_t[d]	BNRAS Flow	HRT_t	CT_t	BNRAS Flow	HRT_t	CT_t
2.0	7.0	75	150	10.0	55	110	12.5	40	80
4.0	7.0	75	300	10.0	55	220	12.5	40	160
6.0	7.0	75	450	10.0	55	330	12.5	40	240
8.0	7.0	75	600	10.0	55	440	12.5	40	320
10.0	7.0	75	750	10.0	55	550	12.5	40	400
12.0	7.0	75	900	10.0	55	660	12.5	40	480

NOTE: a = mg/L; b = mgd; c = theoretical HRT of basin only, minutes; d = theoretical CT, mg/L•min

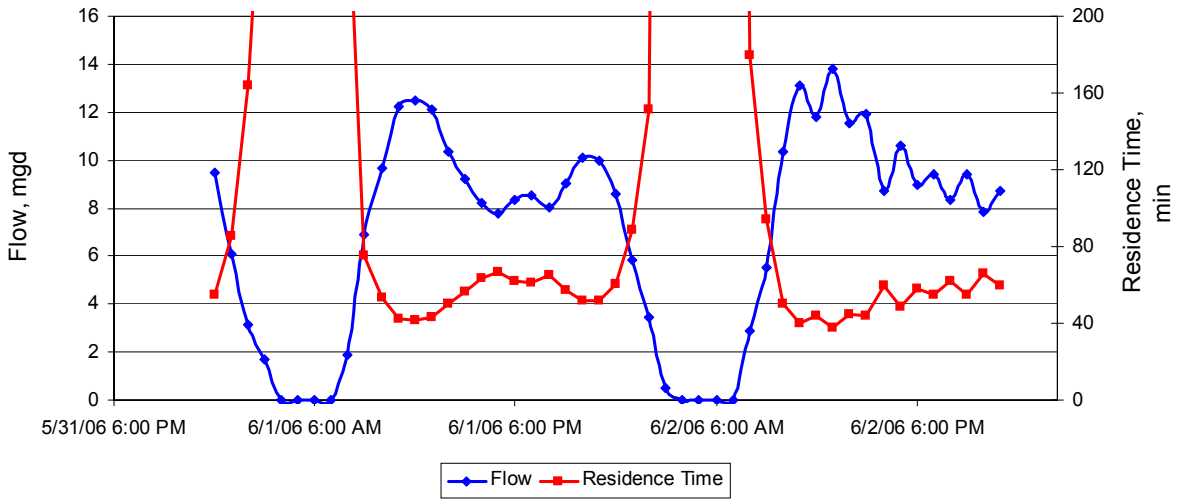
Another observation of the BNRAS chlorination system is that the total chlorine residual registers primarily as free chlorine. This is because the current operation of the BNRAS process achieves essentially full nitrification. Therefore, the amount of chlorine applied to the disinfection process would be beyond the theoretical breakpoint. The applied dosage is likely in the range of 2.5 mg/L. This breakpoint concentration is consequently relatively low.

It is important to note that the presence of significant concentrations of free chlorine increases the potential for the formation of disinfection by-products (THMs) that can have compliance implications. This is particularly critical when employing an enhanced chlorination process because the amount of chlorine dosed is generally much higher than what is being practiced in the current system.

3.1.2 HPO Plant Disinfection System

Similar to the BNRAS chlorination system, the HPO (west) plant's system also utilizes hypochlorite as the disinfecting agent. The chlorine contact basin consists of a serpentine plug flow contact basin. The major difference between the BNRAS and the HPO systems is that the HPO system sees a variable flowrate, reflective of the typical diurnal fluctuations entering the Ina Road WPCF. Because the BNRAS is flatlined at a constant rate, it is not uncommon for the HPO facility to see essentially zero flow for periods of the daily lowest flows in the early morning hours. The theoretical hydraulic residence time for the HPO basin therefore varies widely because of these highly variable flow conditions. Results are illustrated in **Figure 3-3**. For those periods when flows through the HPO reach zero, the theoretical HRT has no physical meaning. This is an important observation because during these periods the chlorine contact basin enters stagnant conditions. Significant residual decay is possible during this time, permitting microorganisms to grow. Secondly, because of the highly variable flow, there is a greater opportunity for solids to enter the basin during high flows, thereby shielding microbes from chlorine exposure.

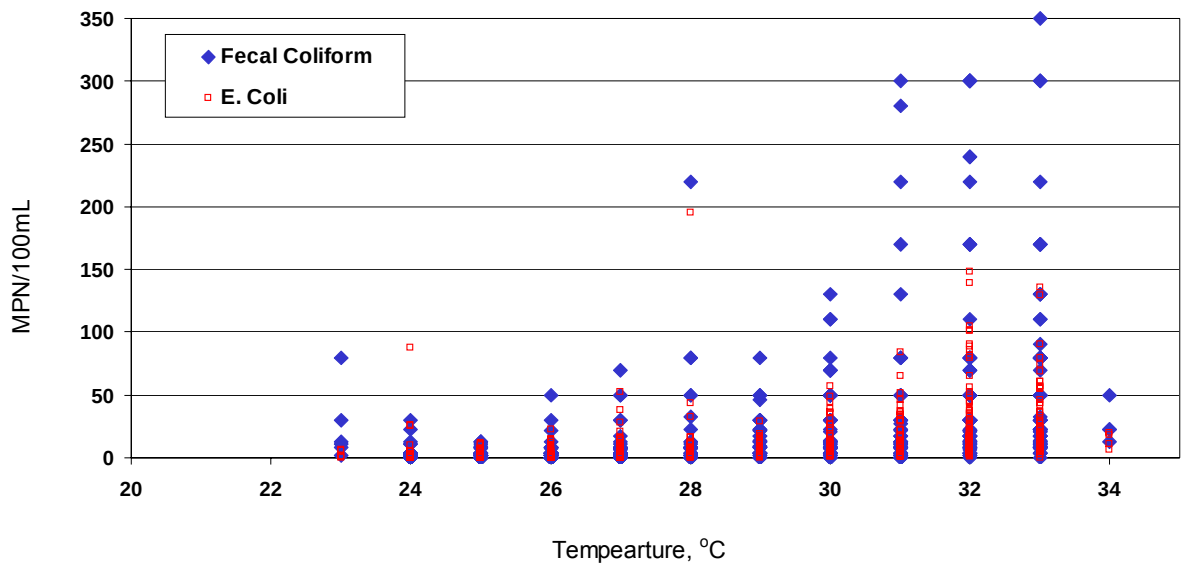
Figure 3-3



In the HPO case, the total chlorine residual consists mostly of combined chlorine, indicating that the HPO plant does not fully nitrify as is expected. Combined chlorine is a less effective disinfectant than free chlorine. Though the chlorine dose applied to the HPO secondary effluent is currently relatively low, it is likely that a much higher dose would be needed to reach breakpoint. Current data indicates that the applied chlorine dose is in the range of about 6.5 mg/L in order to sustain a combined residual of around 2 mg/L.

It should be noted that disinfection at the Ina Road WPCF is also affected by water temperature. In general, data provided indicates that higher fecal coliform and E.coli counts in the disinfected effluent correlate closely with increases in water temperature. This is shown in **Figure 3-4.** This phenomenon may be attributed to several factors. First, at higher temperatures, there is an increase in microbial activity. Secondly, the intense sunlight in the summer months photochemically breaks down available chlorine (primarily in the upper 18-24 inches of the flow depth), rendering the chlorine weaker in disinfection effectiveness.

Figure 3-4



3.2 Studies to Establish Hydraulic Characteristics to Support Enhanced Chlorination

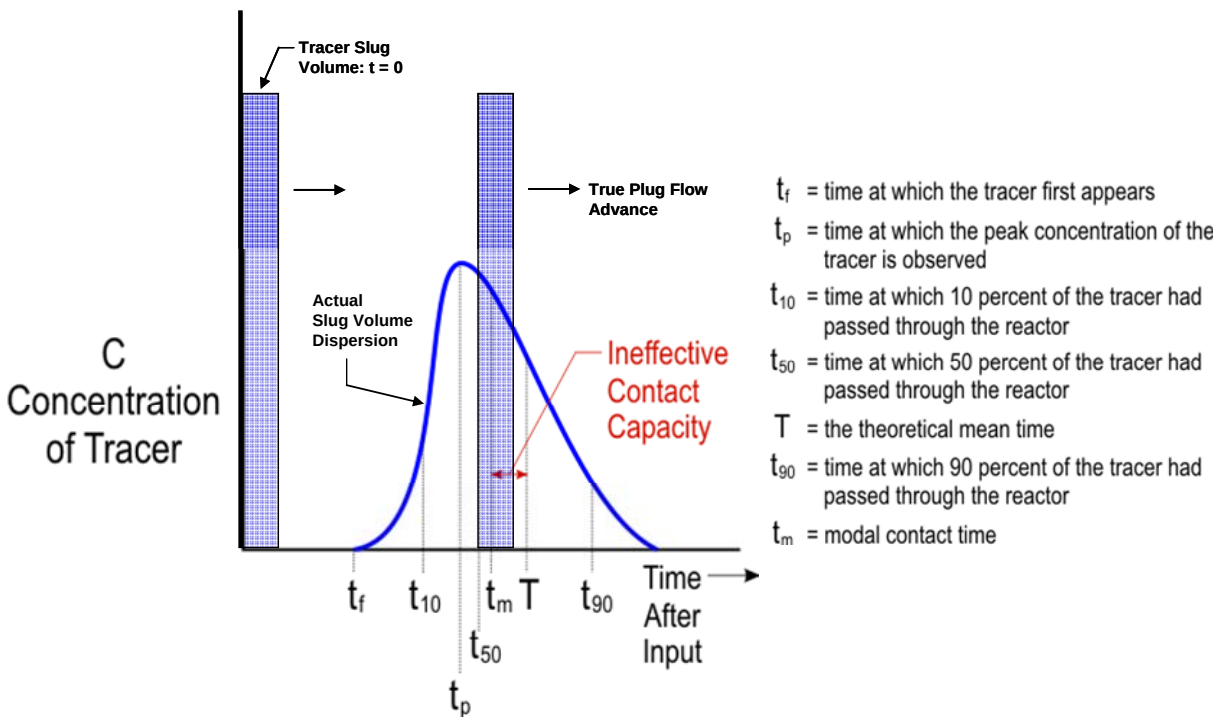
Results of the field assessment of the Ina Road WPCF disinfection facilities indicate that consistent and reliable compliance with BADCT standards requires a thorough evaluation of the existing BNRAS chlorine contact basin hydraulics. Basin hydraulics holds a significant influence over the true time that the target organisms are exposed to the disinfectant dosage.

Hydraulic influence on disinfection efficiency is best described by two fundamental regimes: mixing efficiency and plug flow. In the case of mixing, it is critical that the injected chlorine be thoroughly mixed with the water column of secondary effluent as rapidly as possible at the point of injection. In the secondary effluent there are a number of constituents other than the target organism that create a high demand for chlorine. Therefore, efficient mixing improves the opportunity for chlorine to come in contact with more of the target organisms rather than being lost to other constituent demands. This has an impact on chlorine dose and the resulting downstream contact time required for inactivation reactions to reach completion. It is important, then, to understand how the geometry or the mixing chamber, along with the mixing devices used influence the initial chlorine distribution throughout the water column.

Conventional design of chlorine contact basins provides a large length-to-width ratio to develop as close to a true plug flow condition as possible. In theory, plug flow conditions maintain an optimal concentration of disinfectant in contact with the target organism because plug volume experiences little dispersion. In reality, however, some dispersion of the plug volume does occur. The geometry of the constructed physical tank determines the degree of dispersion. Because of dispersion, some of the flow in a given control plug volume will advance through the basin at a rate faster than the theoretical rate, while other parts of that same volume will pass through slower. These phenomena are a result of different velocities occurring throughout the water column. For example, velocities can differ at the surface than at

the bottom due to temperature gradients changing the fluid's viscosity. Or, friction from containment surfaces creates drag forces on the fluid volume resulting in variable velocity across the flow cross-section. Furthermore, when flows change direction, "dead zones" in the flow path can result. Such unavoidable physical conditions result in a basin flow that can vary significantly from a true plug condition. Such phenomena can be demonstrated with the use of "tracers," which are compounds that do not react throughout the flow path and whose concentration can be tracked along the flow path. This is illustrated in **Figure 3-5**.

Figure 3-5



From this figure several elements are key. First, in a true plug flow system, concentrations of the tracer remain constant as it passes along the flow path. But, in actual physical systems, because of the velocity variations along the flow path, this slug volume "spreads" out, or disperses along the flow path. That portion of the tracer mass that passes out of the system first (noted as t_f in the illustration), in advance of the theoretical hydraulic residence time (noted as T), indicates a "short-circuit" in the flow. The mass passing through last is representative of that portion of the tracer that got "trapped" in zones of low velocity or back-mixing due to localized turbulence. In the figure, this is represented in part by the point noted as t_{90}, which is the time it took for 90% of the trace mass to pass through the system.

Compliance standards generally require the basin contact time used in the "CT" calculation be based on the basin's modal contact time rather than the theoretical contact time. The further a basin's hydraulic regime is from a true plug flow condition, the more will be the spread between the theoretical and modal.

It is important, then, to measure this spread because it provides valuable information for design of the basin.

3.2.1 Field Studies

3.2.1.1 Recommendation: Mixing Efficiency Evaluation

It is recommended that the PCWMD evaluate the efficiency of the rapid mix chamber for the BNRAS chlorination system. This test would utilize a tracer injected through the existing Water Champ® pump and sensors located at different points throughout the mix chamber to measure concentrations of tracer from time of injection. Results of this test will provide important insights into the capability of the existing mixing system to fully mix the disinfectant into the water column in light of the geometrics of the chamber. Furthermore, these results will provide insights into what improvements, if any, to the chamber would be warranted to improve the mixing efficiency.

3.2.1.2 Recommendation: Characterization of Plug Flow

It is recommended that the PCWMD undertake a study to evaluate the degree of dispersion that currently exists in the BNRAS chlorine contact basin. This study would utilize a tracer compound injected into the water column through the Water Champ® pump with sensors located at strategic points along the length of the chlorine contact basin to measure concentration of tracer with time. It is recommended that this test be run under high flow conditions since this will create the least residence time overall and result in the most dispersion due to higher degrees of turbulence in the flow regime. Results of this test will provide the data necessary to calculate the modal contact time for use in true "CT" calculation. Additionally, these results will provide insights into what improvements, if any, to the basin would be warranted to move the flow regime to a more plug-flow-like condition.

3.2.1.3 Recommendation: Basin Flow Velocity Profile

It is recommended that the PCWMD undertake a study that profiles the flow velocity throughout the water column along the basin length. This study would utilize a flow meter instrument that measures flow velocity electronically or mechanically. The profile of the velocity should be done over the entire depth at various points along the basin length. Results of this study will provide insights into where short-circuiting or back-mixing is occurring. These results will provide insights into what improvements, if any, to the basin would be warranted to improve the flow to achieve a more constant velocity throughout the depth profile. This enhances the plug flow conditions. These profiles should be run at both low and high flow conditions.

3.2.1.4 Recommendation: Disinfection Decay Rate

It is recommended that the PCWMD conduct a study that examines the rate and amount of chlorine residual decay along the basin flow path. A sample should be drawn first immediately downstream of the rapid mix chamber to establish the initial residual concentration. Additional samples should then be taken at various points along the basin flow path and the residual measured. It is recommended that samples at each location be taken at several depths. The PCWMD currently owns a HACH® DR2800 unit for measuring chlorine residual. This would be appropriate for this study. The manufacture's specified detection limit for this instrument is 10 ppb, but the actual method detection level is calibrated at 29 ppb.

Results of this analysis will provide insight into the actual effectiveness of the inactivation upstream as the water moves through the basin with time. These results will also provide insights into what improvements, if any, to the basin would be warranted to improve the sustainability of appropriate chlorine residual concentrations throughout. These profiles should be run at both low and high flow conditions.

4. Conclusion

4.1.1 Concluding Opinion

From the literature and assessment findings discussed in this report, the following basic conclusions can be drawn.

- Employment of an enhanced chlorination process for disinfection has a reasonably high probability of success in meeting the current BADCT standards
- Without filtration as a precursor process to disinfection, it is likely that the enhanced chlorination system can consistently meet the 4-day non-detect criteria for fecal coliform; but it is unlikely that it will not consistently meet the maximum limits for fecal coliform and E.coli
- Concern is raised with fully nitrified effluents resulting in free chlorine being the dominant residual species; this has implications on disinfection by-product formation that may impact reliable compliance with WET or other permit limits.

4.1.2 Recommendations

It is recommended that the PCWMD conduct a number of laboratory and field studies to better characterize the system's capability in meeting the BADCT and permit requirements. These include:

- Disinfection kinetics study
- Target organism characterization study under variable flow and solids conditions
- In-situ disinfectant mixing study
- In-situ dispersion study
- In-situ velocity profile study
- In-situ chlorine residual decay study

Appendix G

Enhanced Chlorination / De-Chlorination

Phase II – Field Studies

Pima County
Wastewater Management Department
Regional Optimization Master Plan

Enhanced Chlorination Study
Phase II – Field Studies

October 2007

GREELEY AND HANSEN

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Executive Summary

Pima County Wastewater Management Department (PCWMD) has been developing a regional master plan for the collection and treatment of wastewater to address the growing demands for wastewater services throughout its entire service area. An element of this planning is determining what wastewater treatment processes will be most effective in meeting the needs and objectives of the department while at the same time satisfying requirements regulating the ultimate reuse of the treated wastewater throughout the course of the planning horizon period.

The quality of the treated wastewater effluent defines its ultimate reuse, and a critical quality element is the degree to which potentially harmful bacteria and other microorganisms are destroyed prior to discharge. The State of Arizona has adopted a set of technology-based standards that must be achieved for an effluent to be considered acceptable for discharge. These are known as "Best Available, Demonstrated Control Technology," or BADCT, standards. The current BADCT standards can be summarized as follows:

> the treated effluent must maintain a level of quality whereby the presence of the target microbial organism, *Escherichia coli*, shall not be detected in at least 4 out of 7 samples taken daily over a 7-day calendar week, and, the maximum allowable presence of *E.coli* in any single sample shall not exceed 15 MPN/100 mL.

There are currently a number of disinfection technologies available capable of consistently and reliably achieving the degree of effluent quality required by the current BADCT. Among these are filtration followed by ultraviolet (UV), ozonation, advanced oxidation (using mixed oxidants), membranes, and enhanced chlorination. PCWMD carefully evaluated the alternatives and determined that both the filtration/UV and the enhanced chlorination processes best suited its planning objectives. However, because of the high capital, operational and maintenance costs associated with the filtration/UV process, PCWMD determined that an evaluation of the feasibility of enhanced chlorination as the disinfection process for its wastewater treatment facilities was justified.

PCWMD's evaluation of the enhanced chlorination process is the subject of this report. The evaluation includes literature reviews along with a series of bench-scale and full-scale studies conducted at the East Biological Nutrient Removal Activated Sludge (BNRAS) Plant at the Ina Road Water Pollution Control Facility in Tucson, Arizona. The bench-scale studies established the baseline kinetics for the chlorination process. The full-scale studies estimated the performance limitations of the existing system in meeting current BADCT under specific conditions. The concluding opinion from this feasibility evaluation is that the enhanced chlorination technology is acceptable for implementation as the preferred technology for existing and proposed disinfection systems at PCWMD wastewater treatment facilities within the jurisdiction of PCWMD.

Together these studies provide the information necessary to establish: 1) recommendations for improvements and upgrades to the existing disinfection system at the East BNRAS Plant at Ina Road WPCF necessary to achieve current BADCT requirements, and 2) a set of criteria guidelines for the design of future PCWMD wastewater disinfection facilities to reliably and consistently achieve BADCT standards as currently promulgated

1. Introduction

1.1 Background

Pima County Wastewater Management Department (PCWMD) currently owns, operates and manages a number of wastewater treatment facilities. Over the past year, PCWMD has been involved in the development of the Regional Optimization Management Plan (ROMP). This plan involves evaluation of the Pima County wastewater treatment facilities with key objectives including:

1. Collection and treatment capacities to accommodate population growth throughout the region, and

2. Evaluation of the treatment technology necessary to achieve compliance with Arizona's current and foreseeable future environmental water quality standards for discharge of treated effluent to waters of the state or for reuse.

Addressing the disinfection of the plant effluent with respect to the latter objective is the focus of both the Phase I and Phase II reports. Phase I involved two key elements. First, an investigation of the published literature on disinfection processes was conducted. The purpose was to establish the relationship between the process of chlorination of wastewater effluent and compliance with standards that regulate the water quality for discharges of treated effluent. The objective was to identify facilities comparable in size and process configuration to that of the Ina Road Water Pollution Control Facility (WPCF) and categorize the processes used for treatment and disinfection in the context of their respective compliance standards. Secondly, Phase I gathered information on the existing conditions chlorination facilities at the Ina Road WPCF. This information provided guidance for recommendations on studies necessary to assess the feasibility of an enhanced chlorination process at Ina Road capable of reliably meeting the "Best Available, Demonstrated Control Technology" (BADCT) standards for disinfection set by the State of Arizona. The compliance standards are outlined in the State of Arizona's Administrative Code for environmental regulations.

The results of the literature review in Phase I provided the following general conclusions:

- Employment of an enhanced chlorination process for disinfection has a reasonably high probability of success in meeting the current BADCT standards;

- Without filtration as a precursor process to disinfection, it is likely that the enhanced chlorination system can consistently meet the 4-day non-detect criteria for fecal coliform; but it is unlikely that it will consistently meet the maximum limits for fecal coliform and *E.coli*;

- Concern is raised with fully nitrified effluents resulting in free chlorine being the dominant residual species; this has implications on disinfection by-product formation that may impact reliable compliance with WET or other permit limits.

The results of the field assessments in Phase I generated a set of recommendations for studies to be conducted to better characterize the system's capability to meet the BADCT requirements and establish

the scope of enhancements to the physical disinfection system components and process necessary to ensure consistent BADCT compliance. These were:

- Disinfection kinetics study
- Target organism characterization study under variable flow and solids conditions
- In-situ disinfectant mixing study
- In-situ dispersion study
- In-situ velocity profile study
- In-situ chlorine residual decay study

This Phase II report examines the disinfection efficacy of the existing disinfection technology (chlorination by liquid sodium hypochlorite) employed at the BNRAS (East) Plant at the Ina Road WPCF for achieving future compliance with the BADCT standards for disinfection. The study results reported herein focus only on the inactivation effectiveness of the existing disinfection system for *E.coli*. Specifically, these standards are non-detectable in 4 out of 7 samples per calendar week and a single sample maximum of 15 *E.coli*/100 ml.

Issues surrounding compliance with the state's water quality standards for treated effluent chlorine residual and Whole Effluent Toxicity as required by the Arizona Pollutant Discharge Elimination System (AZPDES) permit issued to PCWMD were not part of these field studies. Similarly, potential issues of concern regarding the formation of disinfection by-products and enteric virus inactivation to address compliance with meeting "Class A" water reuse standards (through the Aquifer Protection Permit) were not addressed in these studies.

The set of study results described herein focus on assessing enhanced chlorination as a technology system for disinfection capable of meeting PCWMD's microbial inactivation compliance objectives reliably and consistently.

1.2 Study Descriptions and Protocols

As described in the Phase I report, two types of studies in Phase II were conducted: 1) evaluation of the kinetics of microbial inactivation for the secondary effluent using bench and full-scale studies; and 2) evaluation of the mixing of the injected chlorine with the influent, the subsequent flash mixing, and the flow regime characteristics of the existing BNRAS chlorine contact basin (CCB). The set of field studies recommended in Phase I involving chlorine residual decay along the flowpath of the CCB and vertical profiles of the flow velocity in the CCB channel were not conducted in Phase II.

Protocols typical of these types of studies are detailed in **Appendix A** of this report. Data analyzed from these studies was collected during the period between May 1 and August 31, 2007.

1.3 Study Participants

The raw data supporting the kinetics studies was collected by PCWMD laboratory staff. Microbial testing was conducted by PCWMD laboratory staff in PCWMD laboratory located at the Ina Road WCPF. Staff also collected information on physical and chemical characteristics of the secondary effluent (such as water pH and temperature) to define baseline conditions. Methods of laboratory analysis were in accordance with the most recent edition of *Standard Methods*.

Participation in these studies by PCWMD operations staff was also significant. The mode of operation currently employed for the BNRAS plant is a "flat-lined" flow condition. For the period between August 2 and August 17 the operations staff modified the raw wastewater pumping operations to simulate the typical influent diurnal pattern through the BNRAS plant. This simulated a more "realistic" condition for the operation of the disinfection process under study, and is reflective of future operations for this facility.

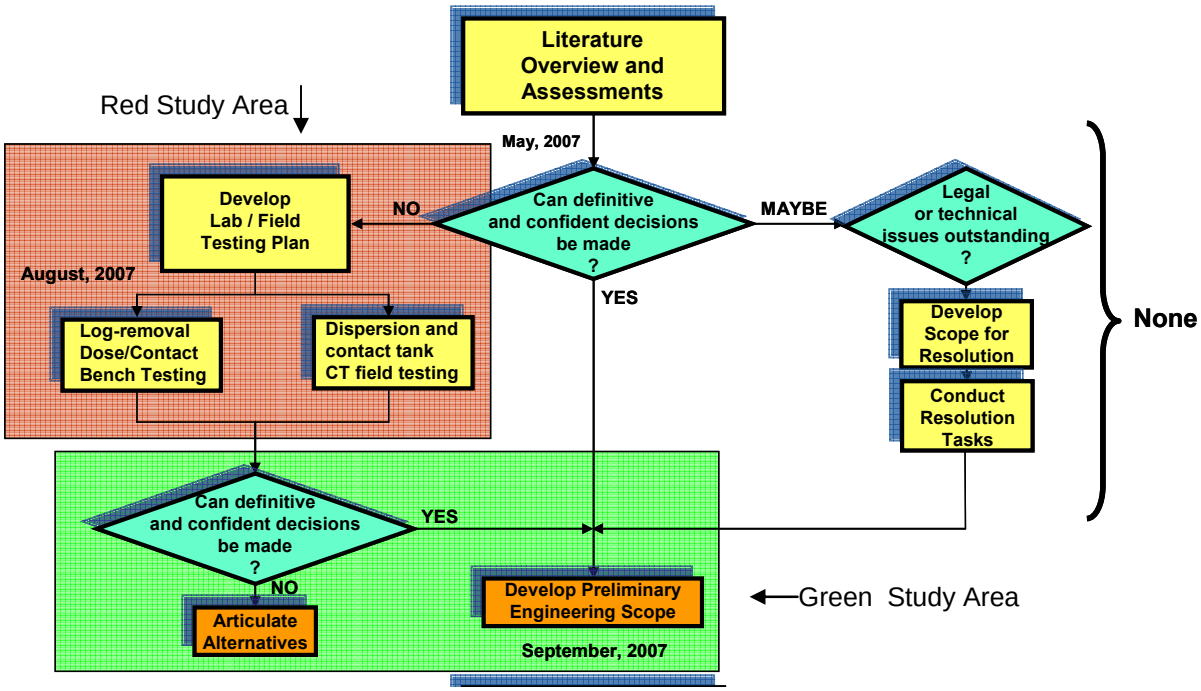
A team of consultants were available to assist PCWMD staff in developing the study protocols and in preparing for the studies. This consultant team was responsible for data analysis and interpretation, and in developing the conclusions and recommendations. These consultants included professionals from the following firms:

- Greeley and Hansen Engineers
- Kennedy/Jenks Consultants
- Brown and Caldwell
- Malcolm Pirnie Environmental Engineers and Consultants

1.4 Decision Process

The decision-making process used for this Enhanced Chlorination Study is repeated here from the Phase I report and is shown on **Figure 1-1.**

Figure 1-1
Decision Process for Enhanced Chlorination Evaluation



The red and green-shaded areas indicate the portion of the decision process related to the studies addressed in this report. A key element in this process is the decision point on whether or not to proceed with the enhanced chlorination technology process. It should be noted that PCWMD indicated that no unresolved technical or legal issues with respect to regulatory framework remain that would inhibit the decision-making steps (as indicated on the right side of decision flowchart).

2. General Technical Approach

2.1 Technical Concepts of the Studies

The primary objective with utilizing chlorine as the disinfectant is achieving the appropriate "CT" (chlorine residual concentration measured at the contact basin outlet x contact time within the basin) range that ensures the degree of inactivation of microbes necessary to comply with the BADCT standards. The amount of chlorine residual measured is related to the kinetic behavior of the inactivation reactions. The actual dosage required to achieve that residual can then be inferred from these results. The contact time is determined from analyzing the characteristics of the mixing of the disinfectant into the bulk liquid and the subsequent flow regime that influences the amount of time the target organisms are in direct contact with the disinfectant. The combination of these two parameters defines the CT. The amount of CT required is therefore the primary parameter driving decisions for design of the chemical feed system and the contact basin.

The focus of these studies was on *E.coli* as the target organism, and determining the appropriate CT for reliably achieving the degree of inactivation of this organism necessary to meet the BADCT standards at the final effluent's point of compliance monitoring.

2.2 Disinfection Kinetics

Kinetics refers to the rate, or speed of a reaction. Important to this rate is the time that the target organism is in contact with the disinfectant, i.e., the longer the contact time, the greater the degree of kill. This can be represented schematically on **Figure 2-1** for chlorine as the disinfectant. The relationship between the contact time and the applied dose of disinfectant is illustrated by the slope of the line.

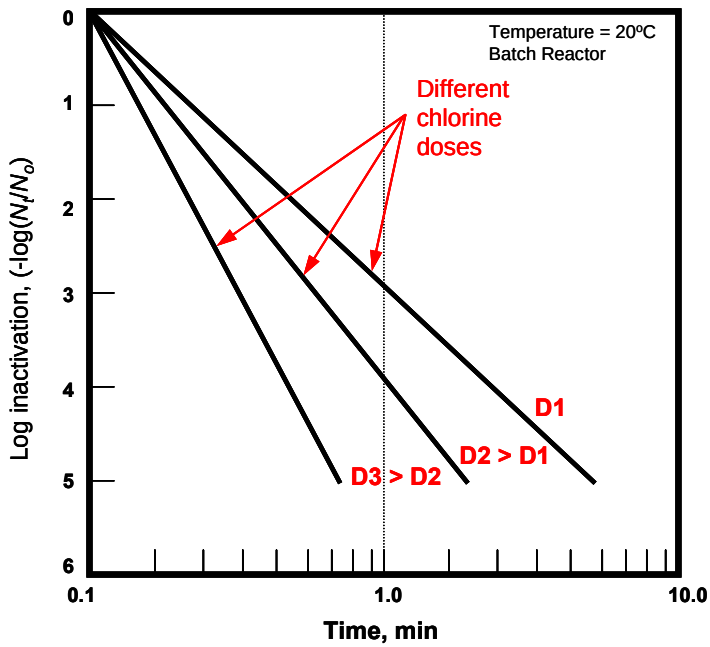
Under ideal conditions, when no outside interferences are present, the rate of change in the concentration of organisms with time is a function of both the number of organisms present and the concentration of the disinfectant residual at any given time. An example of a mathematical model describing this is given in Equation 2-1 (derived from work done by Crick and Watson in the early 1900s). When the solution to this differential equation plots as a straight line on a log-log graph, the inactivation reaction is said to be "1st Order."

$$(dN_t / dt) = - k' C^n N_t, \qquad \textbf{Eq. 2-1}$$

where: (dN_t / dt) = the rate of change in the concentration of organisms with time;
k' = coefficient of die-off
C = concentration of disinfectant measured at time, t
n = coefficient of dilution
N_t = number of organisms at time, t

In the normal environmental conditions encountered in the disinfection of wastewaters, deviations from the mathematical model's ideal conditions are typical. In chlorination systems, these deviations can be related to the microbes' ability to resist the disinfecting power of the chlorine, the presence of organic or inorganic compounds that create a demand for the chlorine, and the presence of particulate matter that encapsulates the organism thereby shielding it from coming into contact with the chlorine. The results of the kinetic response deviate from the ideal response as shown in the figure below.

Figure 2-1[1]
Ideal 1st Order Inactivation in Response to Variable Dose



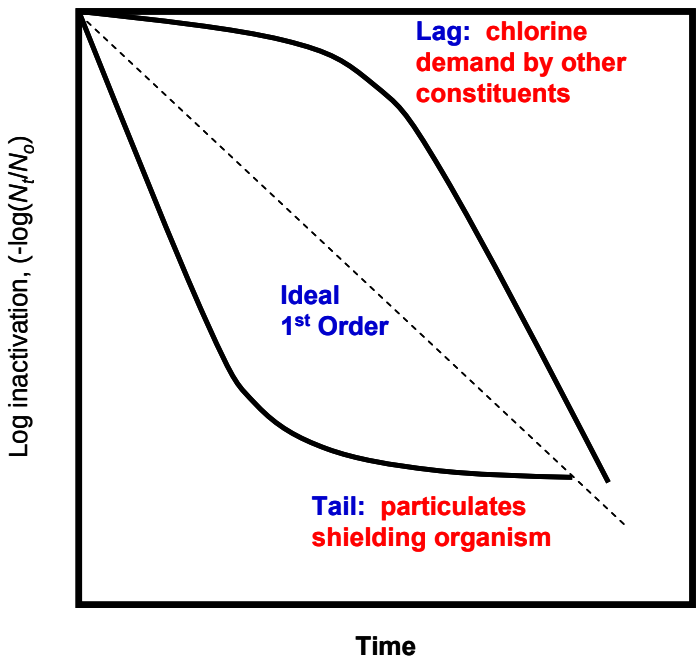
In the disinfection of treated wastewater effluents, the kinetic response is influenced by the type and efficiency of the upstream treatment process. For instance, when significant numbers of higher trophic organisms are present, such as protozoa and algae (sometimes referred to "multiple-hit organisms"), then more chlorine is needed for their destruction before inactivation of the target organism begins to dominate. Another example is when the upstream biological treatment process only partially nitrifies. In this case, the presence of ammonia and/or nitrite in the secondary effluent entering the disinfection facility will immediately react with the available chlorine and form chloramines which are less effective in disinfection power. This results in less free chlorine being available for immediate activity and inactivation of the target organism is delayed. This is illustrated with the "lag" curve.

On the other hand, if total suspended solids are present in the secondary effluent, these tend to provide a "shield" for the target organisms that may be embedded within the floc particle. As a result, these organisms may escape destruction altogether. This is the case with the "tail" curve illustrated in **Figure 2-2.** For this case, the inactivation of the exposed target organisms is immediate. But once these are destroyed the remaining concentration of viable organism declines slowly or not at all due to the shielding effect of the solids. It should be noted that this "tail" curve can also be indicative of the variety of microbial species present, some having a higher sensitivity to chlorine and others being more resistant. For this situation, the "tail" curve illustrates how the more sensitive organisms are destroyed immediately upon exposure, while the more resistant survive much longer. Because of the heterogeneity of species in a typical domestic wastewater, such kinetic behavior is not unexpected.

[1] Wastewater Engineering: Treatment and Reuse, 4th Edition; Metcalf & Eddy, (2003) McGraw-Hill, pg. 1224

The development of the kinetic behavior establishes a "model" by which predictions can be made on the "theoretical" magnitude of microbial inactivation that might be expected if exposed to a given dose of chlorine for a given period of time for this specific disinfection system. The model is very useful because it shows what performance levels are probable, which can then be compared directly with what is actually observed in the field. For instance, if the model predicts that a specific magnitude of inactivation is expected for a given dose and contact time, but the actual observed inactivation in the field is less, then the logical conclusion is that the enhancements to the full-scale system may be necessary in order to bring its performance closer to the model's "theoretical" predictions.

Figure 2-2
Deviations from Ideal 1st Order Inactivation



2.2.1 Kinetic Model Development for BNRAS

To develop the kinetic behavior of the existing disinfection process on the BNRAS secondary effluent, a series of 9 separate trials were conducted over 9 separate days.[2] For each trial, a bulk sample was collected just outside the flash mix chamber of the basin (and therefore subjected to the initial chlorine dose applied by the system at the time of sample). Then, at specific intervals of time from 5 to 90 minutes, individual samples were drawn from the bulk sample, neutralized and tested for Total Coliform and *E.coli*. Enumeration of these target organisms was performed in triplicate on each interval sample and the results average and then plotted.

[2] Sampling and laboratory analysis conducted by PCWMD staff

Because *E.coli* is a subset of Fecal Coliform (FC), and FC a subset of Total Coliform (TC), one would expect some general relationship between the concentrations of these in treated effluent. Indeed, under ideal conditions, as a general rule, TC exceeds FC by approximately 1 log, and FC exceeds *E.coli* by approximately 1 log. Therefore, standard protocol for these types of kinetics studies is to test for TC, FC and *E.coli*. Doing so provides a QA/QC check on the analysis. Due to the fact that the methodology for analyzing FC requires different incubation conditions (and therefore more incubator space), limitations in laboratory resources mandated that the kinetics studies run for the BNRAS disinfection be performed only for TC and *E.coli*.

The set of samples taken over the 9-day period to develop the kinetic model were collected while the BNRAS plant was being operated in an average "flat-lined" daily flowrate of 12.7 MGD (minimum day rate of 12.19 MGD and a maximum day rate of 14.09 MGD). The chlorine dosage applied during these tests ranged between a minimum of 2.88 mg/L and a maximum of 5.12 mg/L of NaOCl as chlorine. The average wastewater temperature at the time these samples were taken ranged from a minimum of 29.7^{o}C to a maximum of 31.1^{o}C, with an average of 30.6^{o}C, and the pH averaged 7.1-7.2. The secondary effluent average suspended solids concentration at the time these samples were taken was < 5 mg/L. The corresponding turbidity of the treated effluent during the test period was less than 2 NTU. This secondary effluent TSS is reflective of good performance of the upstream processes. Obviously, disinfection can be less effective when effluent suspended solids concentrations are much higher than this value.

2.2.2 Full-Scale Kinetic Analysis of BNRAS Secondary Effluent

With the behavior of inactivation kinetics established, the next step was to relate this to the inactivation behavior observed in the full-scale disinfection system. For this analysis, 27 paired samples were collected between the period of May 17, 2007 and July 10, 2007. Each pair consisted of a sample of the BNRAS secondary effluent and the West chlorine contact basin effluent. As with the bench-scale kinetic study, these samples were analyzed for Total Coliform and *E.coli.* The difference in the numerical values from the influent and effluent establishes the "actual" log-inactivation performance being achieved by the system under the environmental conditions present at the time of sampling. By aggregating the data from all valid samples, the result is a range of inactivation efficiencies that can be plotted. From this plot, the degree of actual logs of inactivation being achieved can be estimated for the average, the maximum, and the minimum inactivations. It is important to note that inherent in these results are the variations in flow and process conditions occurring at the time of sampling.

The full-scale kinetic tests were conducted while the BNRAS plant was being operated in a "flat-lined" flowrate mode of in similar fashion to that described in Section 2.2.1 above.

Results and implications from both the bench-scale and full-scale studies are detailed in Section 3 of this report.

2.3 Analysis of Existing Mixing and Flow Characteristics of Chlorine Contact Basin

The time of exposure of an organism to a disinfectant influences its rate of inactivation. Therefore, it is important to understand the operation of the existing chlorine injection system, the initial bulk mixing of the fluid immediately following chlorine injection, and the characteristics of the flow following the initial mixing in the downstream channel of the BNRAS chlorine contact basin.

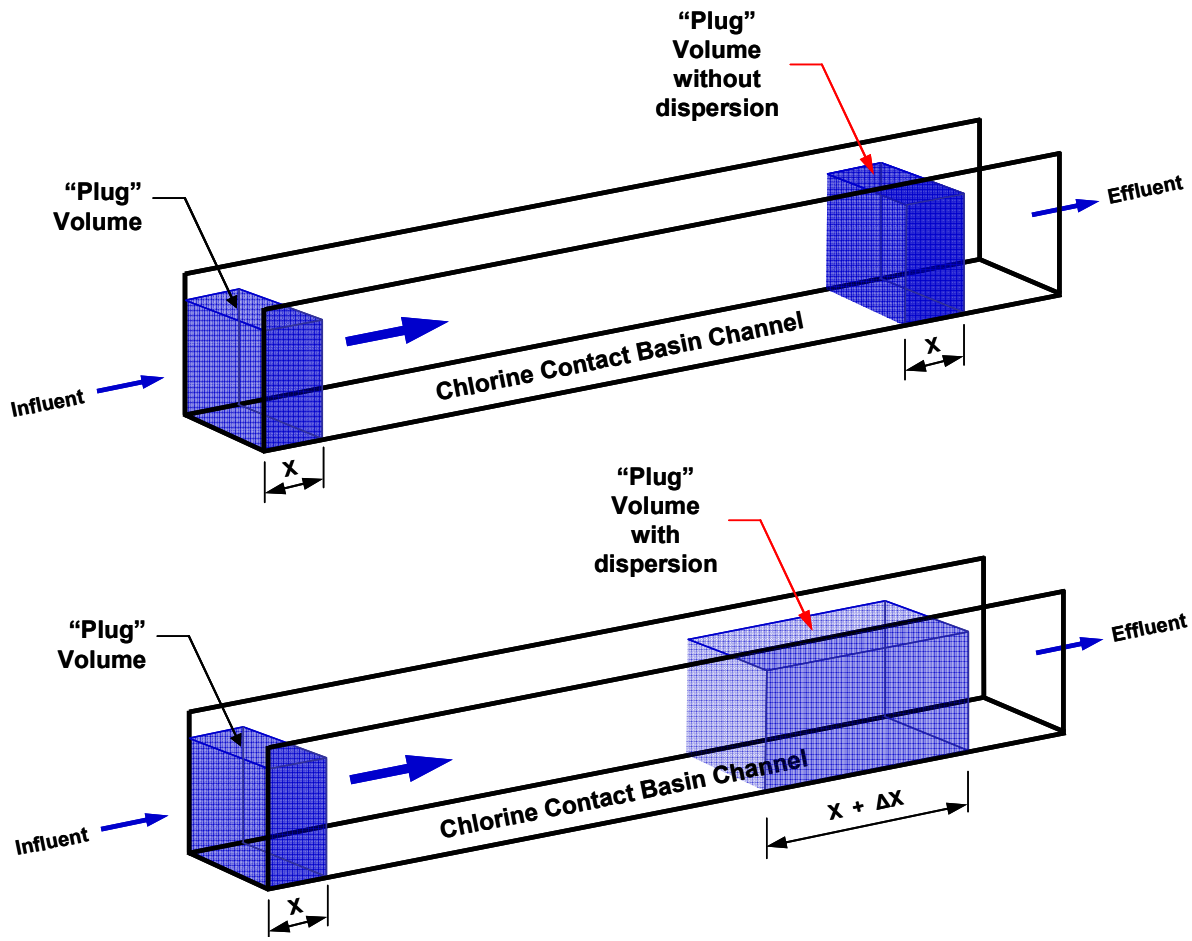
The chlorine injection step and the subsequent intense mixing are crucial to the inactivation of the target organism. As a general rule, efficient injection/mixing regimes that create intense turbulence can increase the overall inactivation efficiencies by as much as 2 logs. Equally as critical is the flow regime downstream of the mixing. Most chlorine contact basins are designed and constructed to operate in a "plug flow" mode. The closer the flow regime is to ideal plug flow, the greater the efficiency of overall inactivation. The greater the length-to-width ratio of the flow channel, the more closely the flow approaches plug flow. For the BNRAS facility, this ratio is approximately 20:1. This value is considered acceptable but at the lower end of the standard for chlorine contact basin design which typically ranges from 20 to 40:1.

Under ideal plug flow, the target organism is held in contact with the disinfectant's maximum residual concentration for the maximum time possible for a given flowrate. If, however, the "plug" volume is dispersed as the flow moves through the contact chamber, the result is a shorter exposure time (due to the hydraulic short circuiting) of the microbes to the disinfectant residual concentration, thereby reducing the overall effectiveness of the disinfection process. This concept is depicted in **Figure 2-3**. In this illustration, a non-reactive compound enters the basin as a plug. Due to non-ideality of flow, the plug volume disperses as it moves through the channel toward the outlet. Near the outlet of the channel, the concentration of the conservative compound at any given point in the dispersed plug is significantly less compared to any point in the non-dispersed plug at the head end of the channel (lighter shade of blue of the dispersed volume at the downstream end represents the lower concentration). In a chlorine contact tank, even if ideal plug flow is achieved, the concentration of the chlorine residual will still be less in the non-dispersed plug volume when it reaches the outlet due to constituent demands and decay of the chlorine itself. Therefore, any deviation from ideal plug flow in a chlorine contact basin results in a more pronounced impact on the disinfection effectiveness.

No physical structure is capable of achieving an ideal plug flow condition. The following are examples of conditions that influence the degree of deviation of a channelized flow regime from ideal plug flow.

- Friction from the channel walls and floor vary the flow velocity across the flow cross section;
- Square corners in rectangular channels built in a serpentine configuration often cause "dead zones" in the flow path;
- Surface winds can create eddy currents that result in back-mixing;
- Temperature gradients can alter the density of the fluid thus affecting its flow characteristic;
- Variation in plant flowrate affects degree of short-circuiting.

Figure 2-3
Concept of Dispersion from Ideal Plug Flow

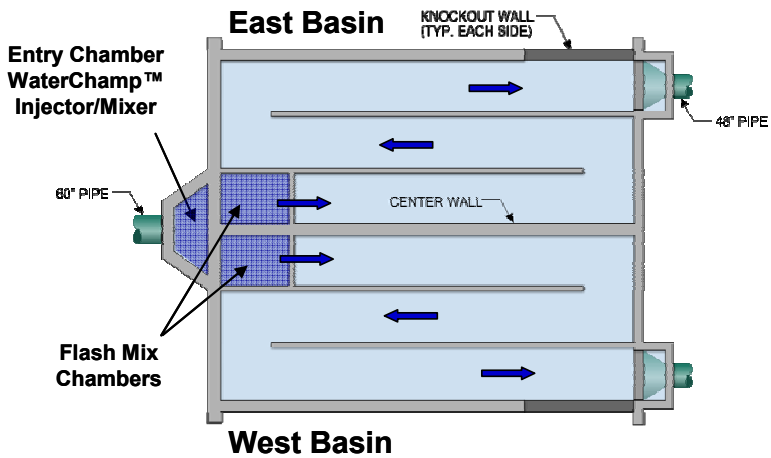


2.3.1 Full-Scale Mixing Analysis of BNRAS Chlorine Contact Basin (CCB)

A tracer methodology was applied to analyze the mixing efficiency of the chlorine injection chamber and the subsequent flash mix chamber of the BNRAS CCB. The location of these two chambers is illustrated on **Figure 2-4** for the BNRAS CCB. The tracer used was sodium chloride (NaCl), a conservative compound that does not react with chlorine and other constituents in water. The concentration of the tracer was monitored by measuring the change in conductivity with time. The salt tracer was injected through the existing WaterChamp™ mixer unit in the "entry" chamber located immediately upstream of the flash mix chamber. The conductivity sensor was first used to profile the tracer over the depth of the injection chamber following injection. The effectiveness of the injection pump in dispersing the chlorine throughout the fluid was determined by the degree of uniformity of the detected tracer throughout the

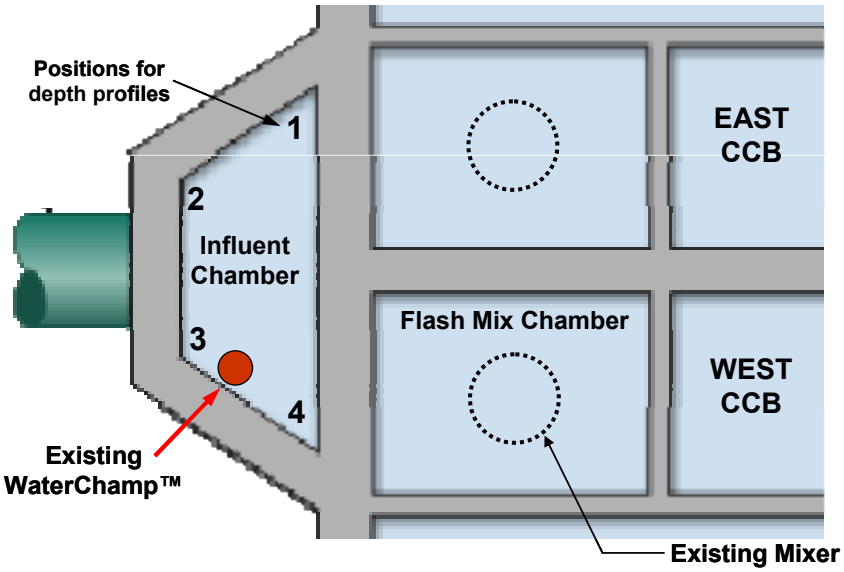
depth at four different locations within the entry injection chamber at specific time intervals following injection. An illustration of these profile locations in the influent entry chamber is shown in **Figure 2-5**.

Figure 2-4
Schematic of Existing BNRAS Chlorine Contact Basin



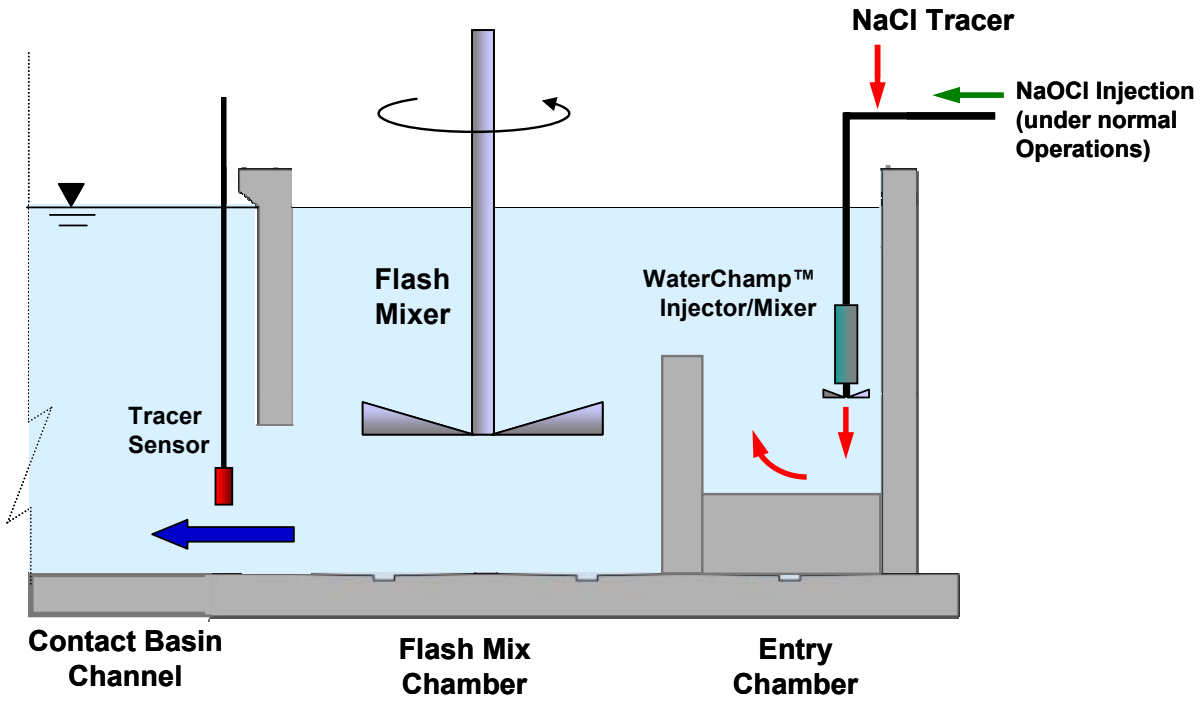
The standard practice of the plant operators for chlorine injection is to inject the sodium hypochlorite (NaOCl) directly into the flow through the WaterChamp™ mixer/pump. However, on the day this tracer analysis was conducted, the WaterChamp™ was not being used for chlorine injection due to a maintenance issue with the pump. The chlorine was instead injected through the existing inductor unit as part of the original chlorinator injector system. This unit is located in close proximity to the WaterChamp™. During the tracer tests, the WaterChamp™ mixer was running but not providing the chlorine injection. The tracer salt was then injected through the WaterChamp to simulate the chlorine injection. The results of the tracer study then, do reflect the WaterChamp's™ ability to mix the contents of the entry chamber.

Figure 2-5
Location of Existing WaterChamp™ Injector/Mixer Unit



Following the chlorine injection in the entry chamber, the flow passes into the flash mix chamber where it is vigorously mixed with a vertical shaft propeller mixer. To determine the effectiveness of this flash mixing, the conductivity sensor was placed at the downstream side of the outlet orifice from the mixing chamber. An illustration of the position of the tracer sensor for the flash mixing data collection is shown in **Figure 2-6**.

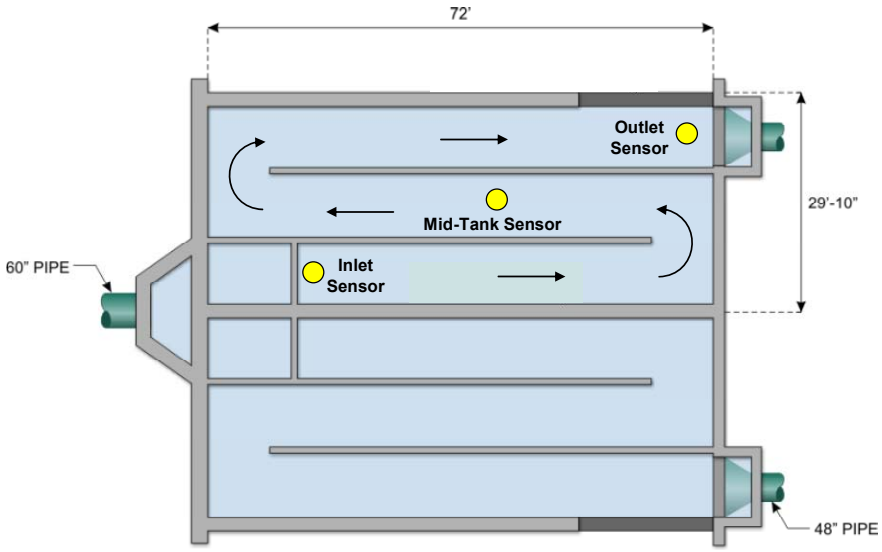
Figure 2-6
Schematic Cross Section of Influent and Flash Mix Chambers



2.3.2 Full-Scale Dispersion Analysis of BNRAS Chlorine Contact Basin

To evaluate how near the channel flow was to ideal plug flow, a NaCl tracer was again used. Three sensors were placed in the channel: immediately downstream of the flash mix chamber, at the mid-point of the channel run length, and just upstream of the effluent weir at the end of the channel run length (see **Figure 2-7**). This was done for both the East and West basins. The brine tracer was introduced through the WaterChamp™ in the entry chamber, typically for a duration of about one minute. Conductivity was monitored at each of these three sensors before tracer was injected to establish the background condition. It was continuously monitored from the time of tracer injection until well after the injection ceased and readings measured at the outlet sensor returned to background levels. The results and implications of these full-scale dispersion studies are detailed in Section 3.

Figure 2-7
Tracer Sensor Locations for Dispersion Analysis

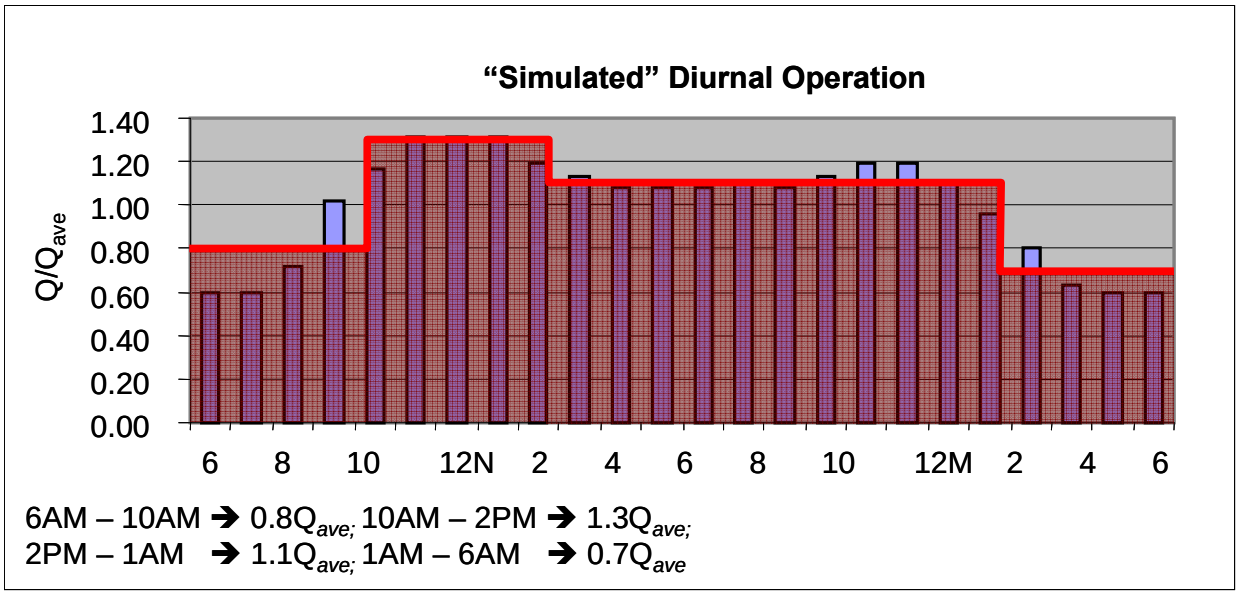


2.3.3 Simulating a Diurnal Flow Pattern

As previously mentioned, the mixing and flow regimes within the CCB vary depending on the plant flow rate at any given time. Therefore, one would expect that there would be a difference in flow characteristics during periods of low flow compared to those of high flow.

The current practice for the BNRAS plant is to operate in a "flat-lined" flow condition. A constant flow of approximately 10 to 12 MGD is processed through the BNRAS plant. In the future, however, the BNRAS facility will operate under normal diurnal conditions, and disinfection will need to be effective under variable flow conditions. Therefore, the project team developed an operational strategy to "simulate" a diurnal flow pattern through the plant. The pattern, illustrated schematically in **Figure 2-8**, was derived from recent historical influent flow data provided by PCWMD. Operators of the BNRAS facility implemented this pattern by manipulating the number of influent pumps in operation at specific times throughout the day.

Figure 2-8
Simulated Diurnal Flow through BNRAS



For both the mixing and dispersion analyses, these tests were conducted during periods of highest flow and lowest flow on the simulated diurnal flow pattern.

3. Results

3.1 Disinfection Kinetics

Disinfection kinetics were evaluated through bench-scale procedures and full-scale measurements. Results from the 9-day bench-scale kinetics and 27-day full-scale kinetics studies are provided below.

3.1.1 Kinetics Behavior

Results from the 9-day bench-scale kinetics study are plotted on **Figure 3-1** and **Figure 3-2**, for Total Coliform (TC) and *E.coli*, respectively. Shown in these figures are the survival ratios of TC or *E.coli*, presented as N/N_0 in log scale, as function of CT. Note that chlorine dosage rather than chlorine residual was used in the CT calculation. Since chlorine dose is higher than chlorine residual due to chlorine demand, this is a conservative approach to estimate the required CT level for a certain efficiency of inactivation.

Figure 3-1
Bench-Scale Results: Inactivation Kinetics – Total Coliform: 9-Day Study

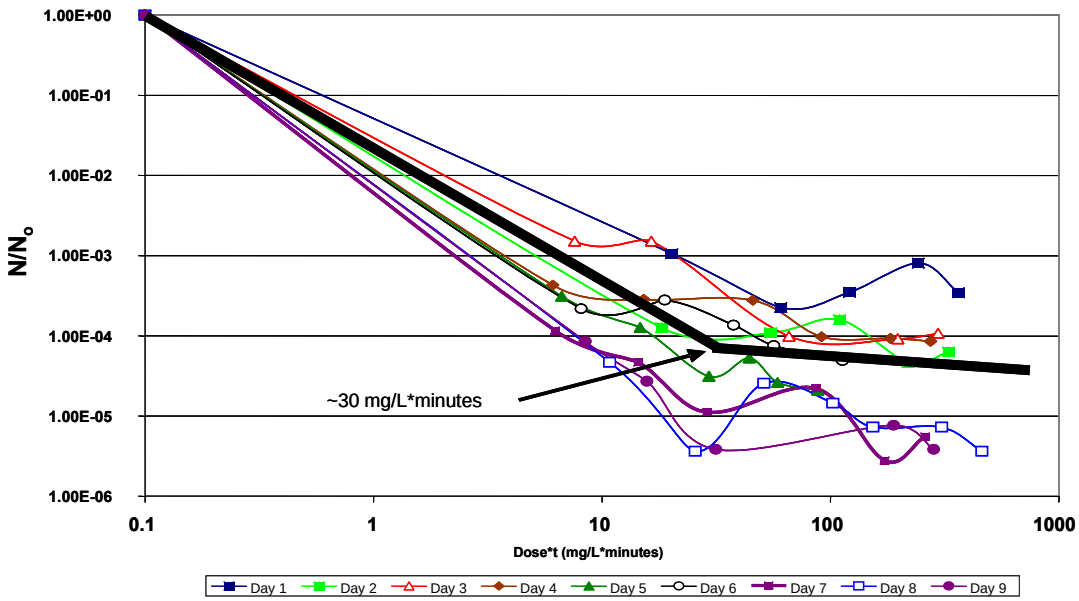
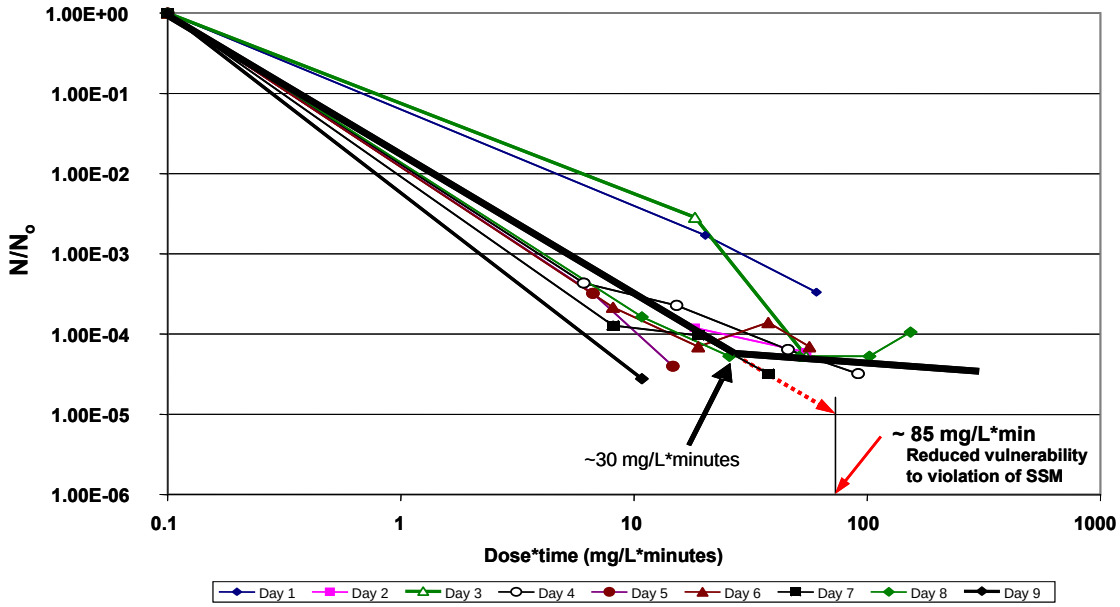


Figure 3-2
Bench-Scale Results: Inactivation Kinetics – *E.coli*: 9-Day Study



The TC kinetics indicates a "tailing" behavior for the inactivation. A trending line (heavy black line) procedure was applied to illustrate the "average" response. For approximately the first 20 minutes of contact time (assuming a chlorine residual of 2 mg/L), the inactivation activity exhibits a 1st Order behavior. But the data then levels out, leaving an "elbow" in the response, and departing from an initial 1st Order reaction. This "elbow" occurs at a CT value of approximately 30 mg/L*minutes, and corresponds to a log inactivation of greater than 4. The presence of the "tail" beyond the elbow depicts a much slower 1st Order response. To explain this slower portion of the disinfection kinetics, the commonly found mechanism is that presence of suspended solids in the secondary effluent. These solids provide some degree of "shielding" of the target organisms from the chlorine inactivation. This "tail" can also represent the resistance of some organisms to chlorine, thereby delaying their inactivation.

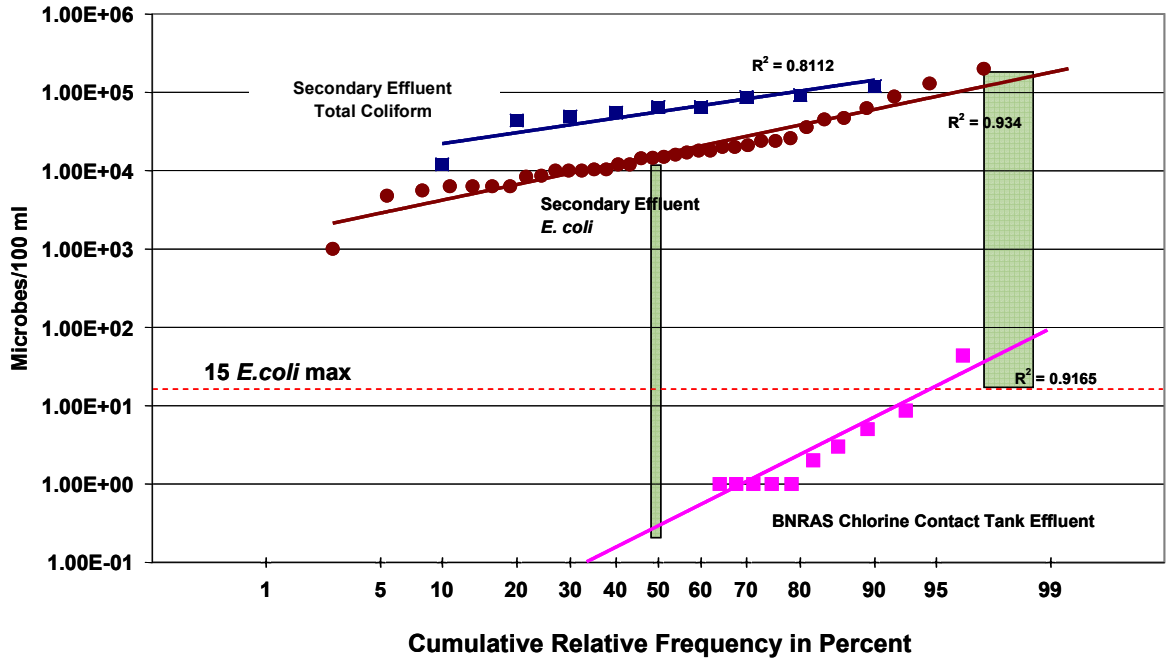
From the bench-scale results for inactivation kinectics a similar behavior is exhibited for *E.coli* inactivation. Because a number of the *E.coli* samples had non-detect results, a "tail" appeared in only two of the nine days. Knowing that *E.coli* is a subset of TC, then we would assume the *E.coli* to follow a similar inactivation behavior as TC. However, the end points on average lie in the 30 mg/L*minutes CT range, similar to that of the TC response, with the log inactivation also being greater than 4. Therefore, the bench-scale results also show the elbow at the 30 mg/L*minutes CT point, and a "tail" having the same slope as that of the TC response. This is a conservative approach since in general one would expect to see the influent CCB *E.coli* concentrations at about two logs less than TC.

The kinetic behavior of inactivation established by these bench-scale results provide important information regarding the magnitude of CT required of the system to achieve the target inactivation levels required by the BADCT. The next step, then, is to analyze the inactivation performance of the existing full-scale system to determine if it is capable of meeting the BADCT. If it is determined that existing full-scale system cannot be relied upon to meet the standards consistently, then enhancements are necessary. These enhancements involve increasing the CT. The amount of increase is provided by the information generated from the bench-scale model.

3.1.2 Full-scale Kinetics Response

Data from the 27-day full-scale study was analyzed and converted to frequency of occurrence ranked by percentile. Using this distribution method, one can determine the "average" inactivations, as well as establish what inactivations are likely for data lying near the "extremes" of the data set. The converted data from the 27-day full-scale is shown in **Figure 3-3**. Performance data is provided in **Appendix B.** During the study, approximately 40% of the effluent *E.coli* counts were found to be "non-detect." These were recorded as "< 1" and though not shown on the graph, were included in the sequencing analysis. Also, to broaden the sample base, the set of 9 secondary effluent samples used in the bench-scale kinetics analysis were included as part of the secondary effluent characterization in this analysis. In the 27-day study figure the solid lines are the "modeled" results and the data points are the observed. The modeled lines are an excellent representation of the observed data as indicated by the very high R^2 values. The modeled results can then be used to project with confidence the extreme conditions, i.e., the portion of the data > 95 percent of the "Z" distribution.

Figure 3-3
Full-Scale Results: Inactivation Kinetics: 27-Day Study



As is evident from the solid lines (the model predictions), the full-scale system is modeled to achieve nearly 5 logs of inactivation of *E.coli* under average conditions (comparing secondary effluent *E. coli* with CCB effluent at the 50th percentile). Even at the 80th percentile, the inactivation is greater than 4.5 logs. This is significant with respect to the BADCT compliance of achieving "non-detect" (ND) 4 out of 7 weekly calendar days. The BADCT requirement means that compliance is met when "non-detect" occurs in at least 57% of the samples during a given 7-day period. Because the reporting limit for compliance is 2 MPN/100 ml, then from this data analysis, the existing full-scale system achieves this requirement 80% of the time. Therefore, the modeled results predict that the current BNRAS design and operation is expected to consistently meet the BADCT's 4 out of 7-day ND requirement.

The graphic also reveals that there are times when the concentration of *E.coli* in the CCB effluent exceeds the BADCT's maximum single sample concentration limit. This maximum limit, 15 colonies per 100 ml, is shown on the graph for reference (dashed red line). The degree of log-inactivation corresponding to the highest *E.coli* concentration detected in the CCB effluent occurs near the 96th percentile. At this point, the modeled inactivation rate is approximately 3.5 logs. This is a critical result. The basic message here is that the existing system is vulnerable to exceeding the BADCT's single sample maximum limit for *E.coli*. To achieve 100% compliance with the single sample maximum limit, an inactivation of more than 4.12 logs would be needed (illustrated by the green bar).

Although only one observed point (i.e., one day out of the 27 days that were tested) on this graph exceeds the maximum limit of 15, this represents one out of 27 samples, or 3.7%. The implication here is that using this observed frequency for a year (365 days), the single sample maximum could be in violation as

much as 14 days. Taking this a step further, applying the 3.5 log-inactivation (modeled inactivation from Full-Scale Results: Inactivation Kinetics: 27-Day Study) to the maximum secondary effluent *E.coli* concentration observed during the study (200,000), would result in a maximum CCB *E.coli* concentration of 66 MPN/100 ml.

The comparison of the degrees of log-inactivation predicted by the frequency distribution model of Full-Scale Results: Inactivation Kinetics: 27-Day Study to that actually observed in the field is tabulated in **Table 3-1**. As indicated, the model's prediction of the degree of log-inactivation exceeds those actually observed for the full-scale system. These results indicate that the bench-scale tests do not adequately reflect the true field conditions, i.e., the physical conditions of the full scale CCB. The implication here is that there is a strong possibility that changes to the full scale system could result in log-inactivation increases necessary to meet all the BADCT requirements.

Table 3-1
Observed Versus Modeled *E.coli* Inactivation for Existing System

Data Source	No. of Samples	Median	Minimum	Maximum
E.coli* detected in CCB effluent (MPN/100 ml)	**10**	**2**	**1**	**44**
Log-inactivation Predicted by model	**10**	**> 5.0**	**3.0**	**> 5.0**
Log-inactivation Observed in full-scale system	**10**	**4.05**	**2.29**	**4.26**

*MPN values rounded to nearest integer

It is very important to take note of the minimum observed log-inactivation value shown in the table, 2.29 logs. This is significantly less than the 3.5 discussed above, a difference of approximately 1.2 logs. This value of 2.29 was the lowest observed *E.coli* inactivation observed during the 27 day trial. For each day, the influent was divided by the effluent to the CCB. There were 10 days when there was a detectable concentration of *E.coli* in the CCB effluent.

To examine the potential impact of the performance of the CCB from another angle, a modeling approach was taken, i.e., the poorest observed inactivation performance (2.29 logs) was applied to the maximum observed *E.coli* CCB influent (200,000/100 ml). If this event ever occurred with the current operation, there would be a concentration of 1,025 MPN/100 ml *E.coli* in the CCB effluent. It should be noted that in review of the observed data set that in fact, in general, the highest CCB effluent *E.coli* concentrations were observed when their paired samples from the BNRAS secondary effluent exhibited among the lowest *E.coli* concentrations.

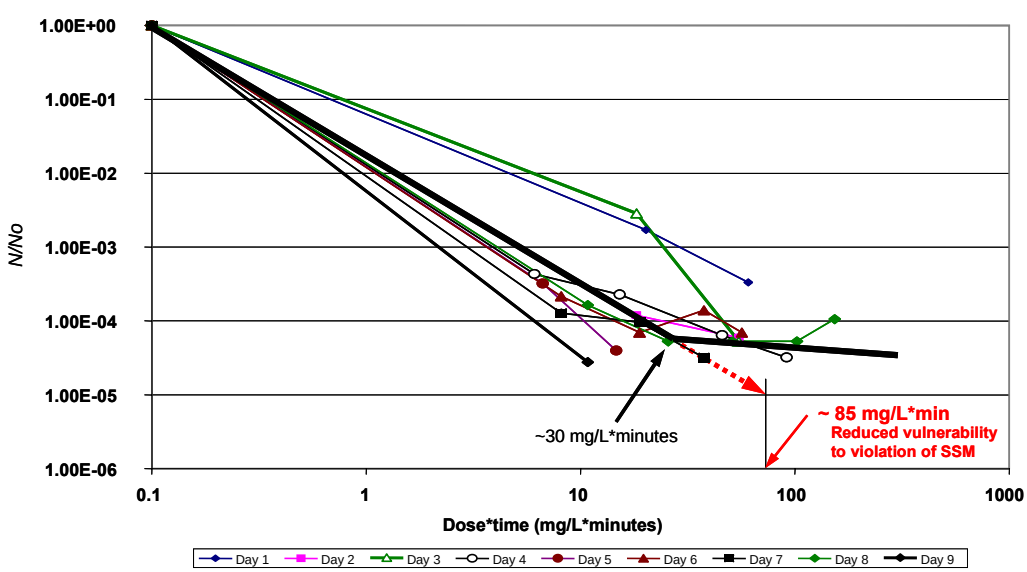
It is noted here that compliance with the maximum *E.coli* limit criterion is subject to the upstream secondary treatment process performance. These analyses were conducted on samples taken at a time when the upstream final clarifiers were performing well, i.e., delivering a treated effluent with total suspended solids below 5 mg/L. Client furnished *E. coli* field data is provided in **Appendix C**.

Therefore, without filtration prior to disinfection, it is crucial that the upstream process be constantly monitored to ensure that its performance delivers the highest quality effluent (especially in terms of TSS) as practical under all flow conditions.

Furthermore, the results of these full-scale kinetic studies are generated from just 27 samples taken from the existing system while operating under "flat line" hydraulic conditions, and taken during that time of year when conditions for optimal disinfection efficiency are least favorable (summer). Therefore, these results do reflect a more realistic "worst case" scenario for this existing system. The consideration of this type of "worst case" condition is appropriate for this overview analysis. The reason is that there were uncertainties with respect to the specific conditions surrounding the plant operations and the secondary effluent quality (such as presence or absence of ammonia, nitrite and nitrate, total suspended solids, water temperature, etc.) during the sampling period.

It is evident from the observed field results that the existing system is vulnerable to violating the single sample maximum criterion. Therefore, enhancing the ability of the existing chlorine system's delivery and reaction environment is necessary. As mentioned earlier, this enhancement must come in the form of an increase in CT. To address this CT enhancement, the *E.coli* inactivation information previously presented is included in **Figure 3-4.**

Figure 3-4
***E.coli* Inactivation Kinetics for CT Projection**



As stated previously, in order to ensure compliance with the single sample maximum criterion, a log-inactivation of greater than 4.12 is necessary. According to the statistical model's predictions (based on the observed field inactivation responses), meeting the single sample maximum requires at least 5 logs of inactivation. Therefore, examining the inactivation kinetics behavior for *E.coli* depicted in the CT

projection figure and extrapolating the 1st Order portion of the response beyond the "elbow", 5 logs of inactivation at a CT of approximately 85 mg/L*minutes can be obtained. This is graphically illustrated in the CT projection figure. Because of the various uncertainties associated with the operational conditions of the plant during the sampling periods, it is recommended that the target CT for achieving the single sample maximum compliance be set at 100 mg/L*minutes at maximum flows.[3]

It is also important to recognize that CT is a function of temperature. In cold temperatures the CT needs to be higher due to slower reaction rates. However, chlorine decay rates in colder temperatures are less than those in warm temperatures. As a result, the slower decay rates in a sense compensate for the slower reactivity rates. The specifics of these relationships were not part of this study. Therefore, assuming the CT target of 100 mg/L*minutes provides a margin necessary to take temperature into account.

Achieving this increase in CT is a function of both the chlorine dosage applied to the system and the subsequent mixing and contact time in the CCB. Increasing dosage is an operational change of minor consequence. Improving the mixing conditions and increasing the contact time in the CCB are modifications that involve mechanical equipment upgrades for the mixing and additional structural elements within the basin itself. These are discussed in more detail in Section 4.

3.1.3 Conclusions from Kinetics Studies

Several conclusions can be drawn from these kinetics studies with respect to BADCT compliance. These are:

- The existing BNRAS chlorine disinfection system is capable of meeting the 4-out-of 7 weekly calendar days Non-Detect permit condition during the test period. On average, it currently meets this more than 80% of the time. The BADCT requires it to be met only 57% of the time.
- Under the current operating conditions and physical facilities, the existing BNRAS chlorine disinfection system is vulnerable to violations of the single sample maximum criterion for *E.coli* (15 MPN/100 ml).
- Bench-scale inactivation kinetics analyses provide guidance information on the amount of CT necessary in the full-scale system to achieve consistent BADCT compliance.
- Modifying the existing BNRAS chlorine disinfection system to reliably achieve a CT capable of meeting the single sample maximum criterion for *E.coli* is necessary and appropriate course of action.
- A CT of at least 100 mg/L*min at maximum flow conditions should be used as the minimum target for sizing and implementing any improvements to the BNRAS chlorine disinfection system to enhance its current performance to ensure compliance with the BADCT single sample maximum criterion for *E.coli*.

[3] It is important to note that the target of 100 mg/L*min at maximum flows implies that the CT for the average flow condition would be likely more in the 140 mg/L*min range.

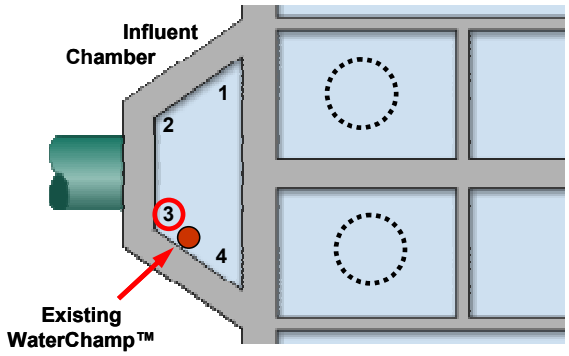
3.2 Mixing and Dispersion Field Studies

Field studies were conducted on the east BNRAS chlorine contact basin to determine mixing efficiencies. The results of the mixing and dispersion studies are provided below.

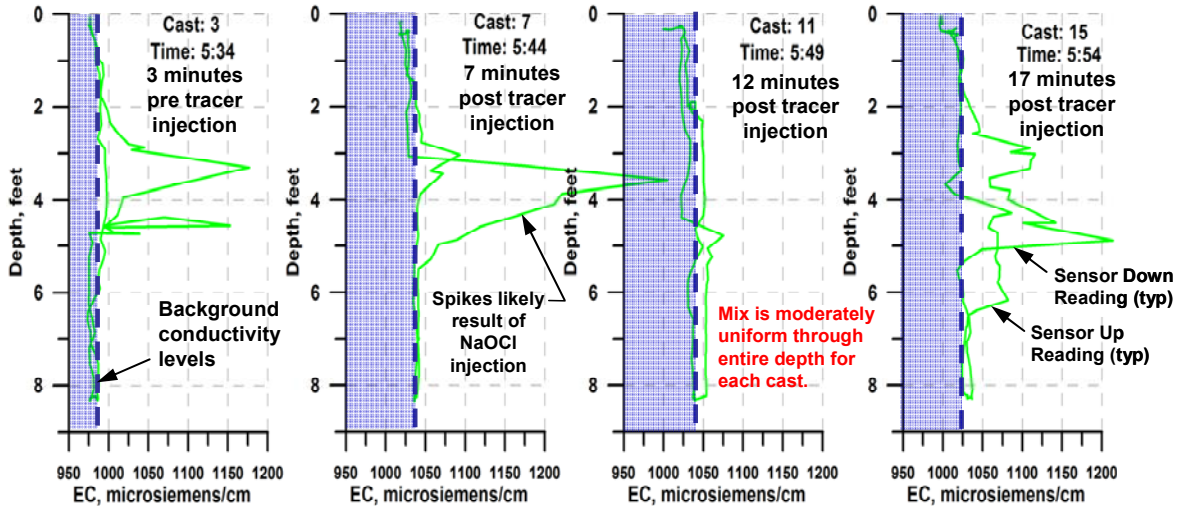
3.2.1 Results from Mixing Analysis of the Entry Chamber for Chlorine Injection

Examples of the results of the tracer injection/mixing study conducted for the entry chamber to the CCB during low flow conditions are shown in **Figure 3-5**. (This particular graph depicting the mixing conditions at position "3" is one of a series of tests run. Tracer compound was injected for a period of 23 minutes through the existing WaterChamp™ mixer/pump located near position "3". Tracer unit sensors were then lowered into the entry chamber to its full depth (approximately 9 feet) at each of the four locations shown in the figure below, and at the times shown relative to the time of tracer injection. Tests were run for both the low flow and high flow conditions, corresponding to 8.8 MGD and 16.2 MGD, respectively, for all four positions. Conductivity readings were taken while the sensor was lowered to the chamber depth and while being raised back to the surface. (This is reason for the two lines appearing on each cast graph.) One "round trip" of the sensor is known as a "cast."

Figure 3-5
Vertical Mixing Profiles: Influent Chamber: Low Flow Condition



Location 3
Brine Release 05:37-06:00



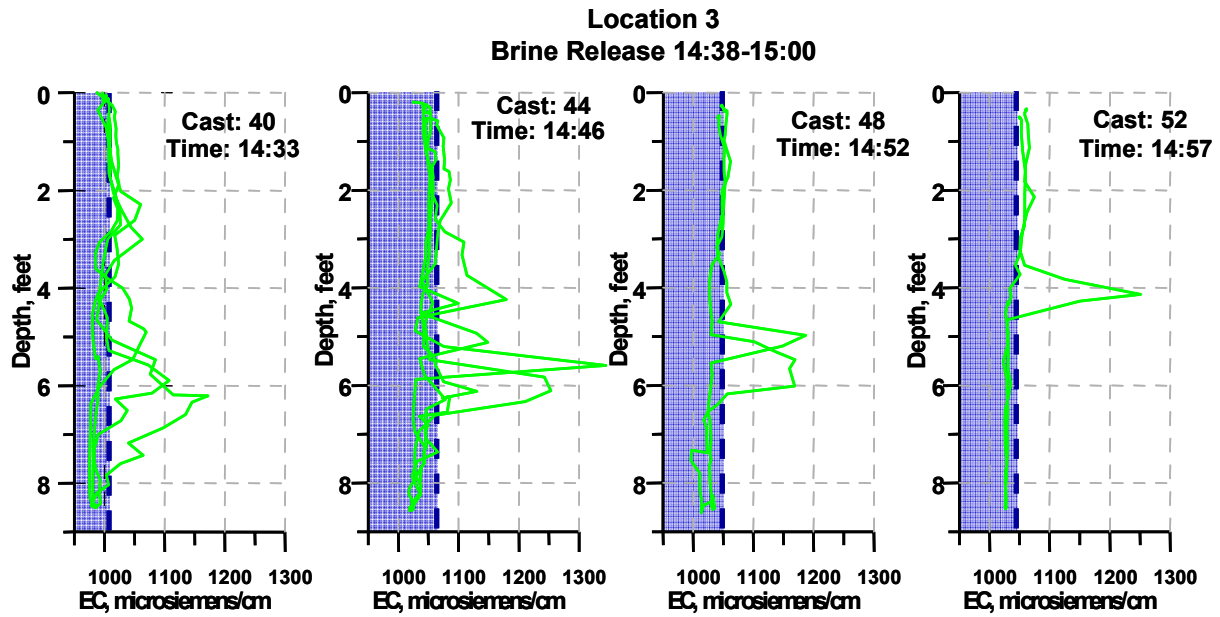
At a depth of about 4 to 5 feet, we observe significant localized spikes in the conductivity readings even before tracer was injected. The likely explanation for these is that the sensors were picking up the influence of the injection of the NaOCl coming into the chamber through the chlorine induction system. The added sodium chloride is what the sensor is reading.

With the spikes "removed" from the data, the remaining data can be reasonably represented by the blue shaded areas. Prior to the time of tracer injection, one observes the background conductivity levels in the chamber. There is a rise in the average conductivity level shown at Cast 7, which is 7 minutes following the start of tracer injection. This rise is relatively uniform throughout the entire depth of the chamber. At 12 minutes post-injection this characteristic remains relatively steady, still reasonably uniformly mixed throughout the depth. At 17 minutes post-injection, there is slight overall decrease in tracer concentration, yet still reasonably uniform throughout the depth. Therefore, in this low flow condition,

the WaterChamp™ mixer/injector unit seems capable of providing reasonably uniform mixing throughout the chamber depth.

Figure 3-6 illustrates the results of a second test at the same position "3" except that this test was run under high flow conditions. Again, the general result is that the tracer appears to be relatively uniformly mixed throughout the chamber depth. However, close observation of the vertical mixing profiles shown below indicates that the concentration of tracer declines slightly at the lower depths compared to the upper depths (see Casts 44 and 48). This indicates that during high flows the WaterChamp™, in its current position orientation, is less capable of mixing uniformly at all depths. This may be indicative of some degree of short-circuiting through the chamber in high flow. The complete summary for the responses at each of the 4 positions are given in **Appendix D**. Each of these illustrates similar responses.

Figure 3-6
Vertical Mixing Profiles: Influent Chamber: High Flow Condition



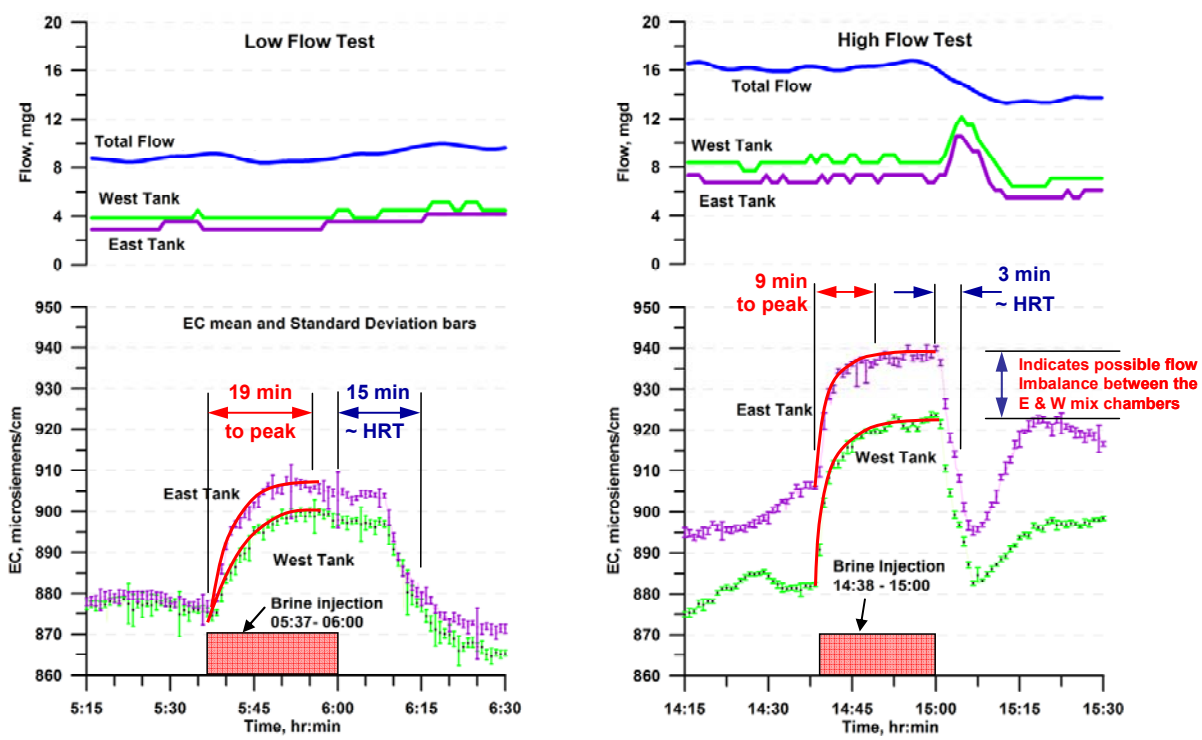
The data indicates that the WaterChamp™ unit is capable of providing reasonably uniform mixing of the entry chamber. However, its performance under the high flow conditions could be better. Its current location near the wall likely hinders some of the jetting action of the propeller due to the interference from the adjacent wall. This interference hinders the even distribution of the mixing energy into all parts of the chamber and throughout its depth, primarily in high flow conditions. The implication here is that in high flow, the chlorine may not be as evenly distributed as it could or should be to ensure optimal opportunity for disinfection effectiveness downstream.

3.2.2 Results from Analysis of Flash Mix Chamber

To gauge the efficiency of mixing provided by the vertical shaft propeller mixers in the flash mix chamber, a conductivity sensor was placed at the outlet orifice of the flash mix chamber and a salt tracer introduced again at a constant rate through the WaterChamp™ in the entry chamber for a period of about 22 minutes. The results of the low and high flow responses are shown in **Figure 3-7**.

A metric of mixing efficiency in this chamber is the time required for the tracer to reach a peak. The more rapid the time-to-peak, the more efficient is the mixing. Also, the hydraulic residence time of the chamber is another gauge of the mixing efficiency. This is most easily estimated by monitoring the time required for the conductivity readings to reach background levels after the tracer injection is ceased. This time is then compared against the theoretical hydraulic residence time for the flow rate at the time of the test.

Figure 3-7
Tracer Study Results: Mixing Regime: Flash Mix Chamber



For the low flow condition, the time-to-peak is estimated at 19 minutes, and the HRT at 15 minutes. Similarly, for the high flow conditions, the time-to-peak is estimated at 9 minutes and the HRT at 3 minutes. A brief lag would be expected in the tracer detection due to the tracer being injected in the entry chamber. However, even accounting for this, the 19-minute time-to-peak during the low flow condition is excessive. This is indicative that back-mixing is occurring in this chamber and is probably being caused

by the large flash mixer unit drawing water back into the chamber via the outlet orifice. In the high flow condition, the time-to-peak is reduced but still longer than an ideal response.

With respect to hydraulic residence time, for the low flow rate condition of approximately 4 MGD passing through the chamber, the estimated HRT is 15 minutes. The theoretical HRT for the mix chamber at this flowrate is approximately 2 minutes, or about 13% of the observed. Similarly, in the high flow condition (~8 MGD), the estimated HRT is 3 minutes. The theoretical HRT for this condition is less than 1 minute, or about 33% of the observed. Clearly, the mixing regime in this chamber is being influenced by significant back-mixing, again, probably caused by the turbulence from the vertical mixers. It appears that the mixer draws flow from the channel immediately downstream of the chamber outlet back into the chamber, thereby delaying the tracer's time to peak and the HRT. The physical implication is that this back-mixing will likely disrupt plug flow characteristics in the channel downstream of the chamber. These results would imply that the action of the vertical mixers may be a hindrance to conditions necessary for optimal disinfection system performance.

Finally, the tests revealed differences in the conductivity readings between the East and West flash mix chambers. These are delineated in the tracer study results. Though differences are present in both low and high flow period, the effect is accentuated during the high flow. A logical explanation for these differences is an imbalance in flow through the two parallel flash mix chambers. Because flow balance analyses were not part of this study effort, the cause of the apparent imbalance was not determined. But it is important to note that this observation was made.

3.2.3 Results of Dispersion Analysis of Chlorine Contact Basin

To initiate the dispersion tests, tracer salt was again injected through the WaterChamp™ unit. Three sensors located at equal intervals along the length of the CCB were used to monitor changes in conductivity with time following injection. The first sensor was centered just outside the outlet orifice, a couple feet above the bottom. The mid-tank sensor was centered in the channel at mid-depth, about 7 feet below the surface. The third sensor was placed at the discharge weir crest just below the water surface. **Figure 3-8 and Figure 3-9** are examples the dispersion test results for the East CCB during low and high flow periods.

Figure 3-8
Dispersion Results – East Basin: Low Flow Condition

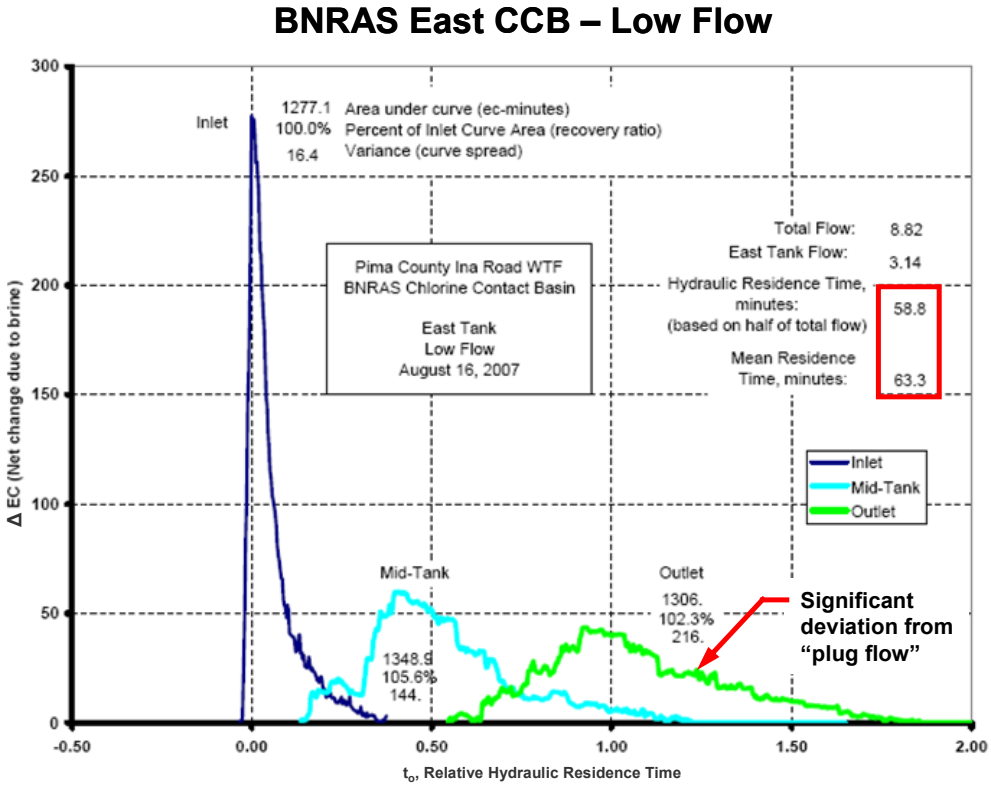
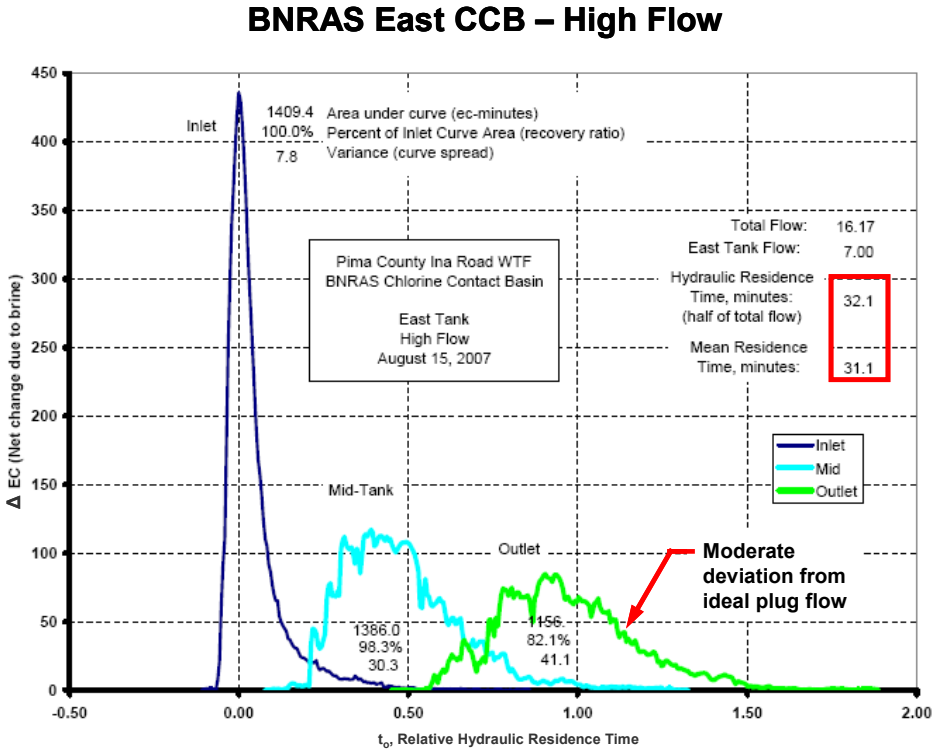


Figure 3-9
Dispersion Results – East Basin: High Flow Condition



The three sensors describe the flow regimes at their respective locations over time. At the mixing chamber outlet location, the peak is narrow and very high. However, even at this location, one observes a "tailing" of the tracer out of the chamber. This affect is an indication that back-mixing is occurring already at this location, another indicator that the vertical mixers are the likely cause. It is interesting to note the significant degree of decline in the peak between the mixing chamber outlet and the Mid-Tank location. This is evidence of considerable back-mixing and loss of a plug flow characteristic in the initial pass of the CCB serpentine channel. However, the peak at the Outlet location shows minimal decline to that compared to the peak at the Mid-Tank. This would imply that this portion of the CCB channel flows in a relatively uniform manner compared to that of the initial pass of the serpentine channel. A qualitative confirmation of this is given in Section 3.2.4 when the results of the drogue observations are discussed.

These dispersion analyses provide insight into the actual hydraulic characteristics for the basins operating under these particular flow rates. By examining the tracer response at the Outlet location, we see that in both low and high flow conditions a portion of the tracer mass passes the outlet location in advance of the theoretical HRT. This is depicted by the "rising limb" of the curve. This indicates that some short-circuiting of the flow volume is occurring. This could be due to more rapid flow velocity at the surface compared to that next to the floor of the channel. With respect to disinfection effectiveness, for that portion of the flow volume that short-circuits, the amount of time the target organism is exposed to the chlorine residual is diminished from its intended design exposure time.

Additionally, the dispersion results show that for both low and high flow conditions there are also portions of the mass passing the outlet beyond the theoretical HRT. This is depicted by the "falling limb" of the curve. This indicates the presence of back-mixing and/or stagnation, likely due to eddy currents along walls and "dead zones" in corners of the rectangular channel cross section. With respect to disinfection effectiveness, for that portion of the flow volume that stagnates in the basin, there will be decay of the chlorine residual, reducing the disinfecting power on the target organisms in those zones.

These observations have implications for disinfection effectiveness. Improvements to the basin are necessary to improve the nature of the plug flow, i.e., reduce the degree of dispersion. These improvements bring the HRT closer to the theoretical during all flow conditions. Doing so allows better control of meeting the target CT. But, variable flow conditions create operational challenges in sustaining the target CT. At low flow, the "T" naturally increases and one might presume that the corresponding chlorine dose could be decreased (from average dose) in order to sustain the CT target. But since "C" represents the chlorine residual at the basin outlet, it is quite possible that indeed the dosage may have to be increased to compensate for any residual decay that may occur. Conversely, at high flow, the "T" naturally decreases, and one might presume that the corresponding chlorine dose should be increased (from average dose) to sustain the target CT. Again, because the "C" represents the chlorine residual, an increase in dosage would be appropriate because a higher residual compensates for the shorter HRT. But this higher residual also requires a concomitant increase in the dosage of the dechlorination agent.

The dispersion test results need confirmation. This can be done by normalizing the tracer mass and plotting it as cumulative mass at each point with time. Examples of this are given in the companion graphs shown **Figure 3-10 and Figure 3-11** for the low and high flow conditions for the West basin. (The complete set of these companion graphs is provided in **Appendix E**).

Figure 3-10
Dispersion Results: Cumulative Mass Curve – West Basin: Low Flow

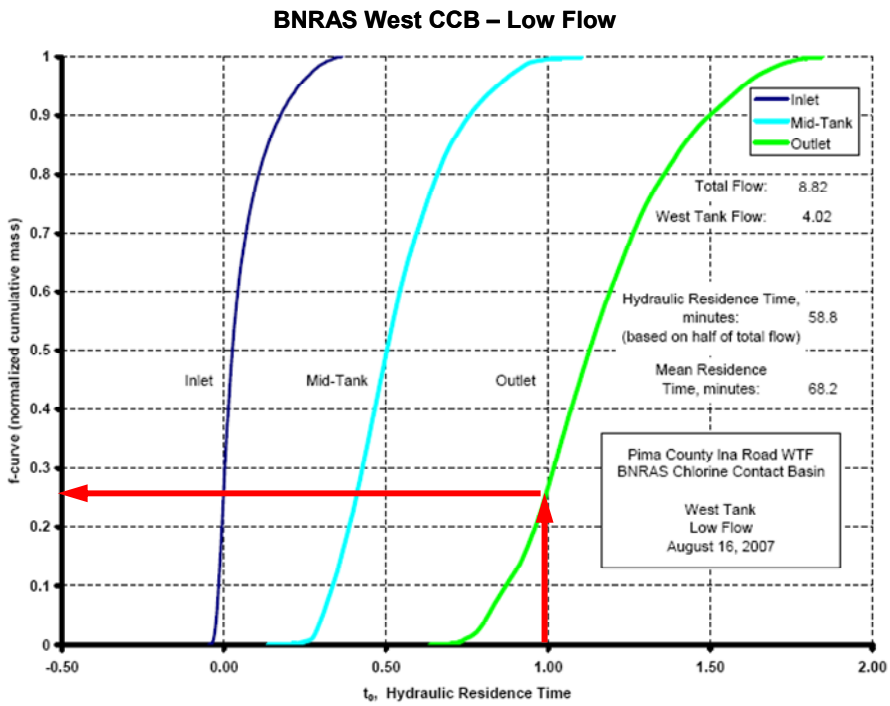
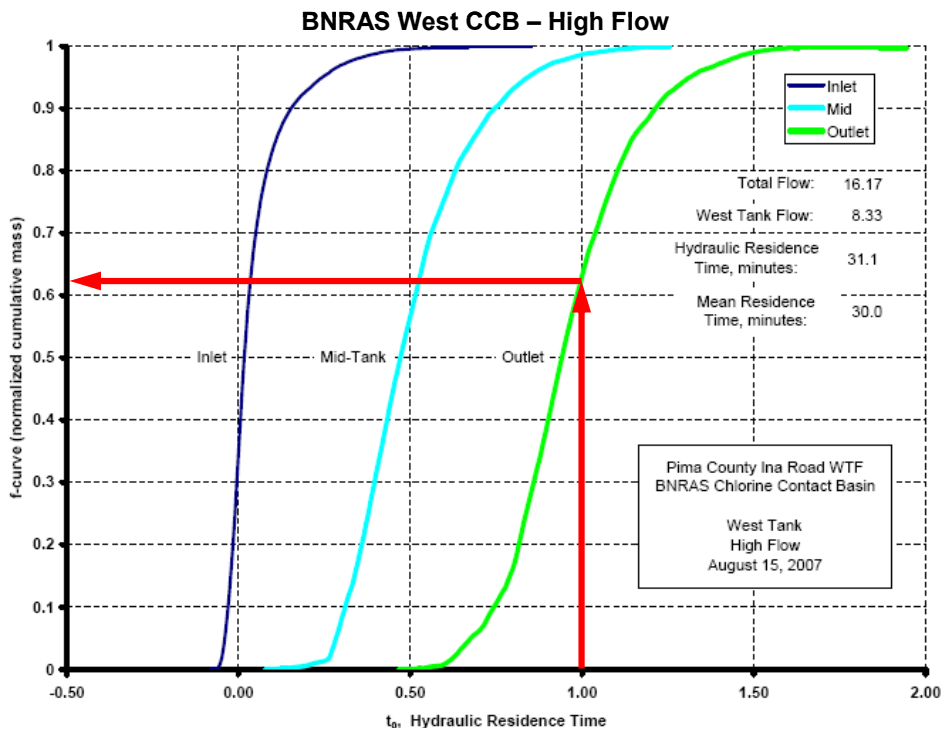


Figure 3-11
Dispersion Results: Cumulative Mass Curve – West Basin: High Flow



For conditions near ideality, the cumulative curve would be essentially vertical at each of the three locations measured. Deviation from vertical is an indication that a back-mixing/stagnation and/or a short-circuiting condition exists for a particular state of flow.

First, consider the low flow condition in the West CCB. Clearly, the cumulative curve deviates significantly from vertical, indicating a less than ideal plug flow condition. The first detection of tracer at the outlet occurs at about 0.75 of the theoretical HRT. Approximately 28% of the tracer mass passes the basin outlet prior to the theoretical HRT (corresponding to the "rising limb" of the plot for dispersion results - East Basin: Low Flow Condition), while the remaining 72% passes after the theoretical HRT (corresponding to the "falling limb" of the dispersion results – East Basin: Low Flow Condition plot). The final reading of tracer occurs at about 1.8 of the theoretical HRT. Interpreting these results, then, we can say that 28% of the flow volume short-circuits while the majority, i.e., 72% of the flow volume "stagnates" during a low flow condition. So, the dispersion of the plug flow in low flow indicates that while the majority stagnates in the CCB, there is still a significant portion of the flow volume that short-circuits (nearly a third). Furthermore, despite the amount of apparent stagnation, both the peak of the tracer mass and the centroid of the dispersed trace mass pass the outlet in advance of the theoretical HRT.

Next, we consider the high flow condition in the West CCB. Here, again, there is a deviation from the ideal plug flow condition. But, in contrast to the low flow curve, the high flow is closer to a vertical configuration. Therefore, it can be argued that the CCB responds closer to ideal plug flow in the high

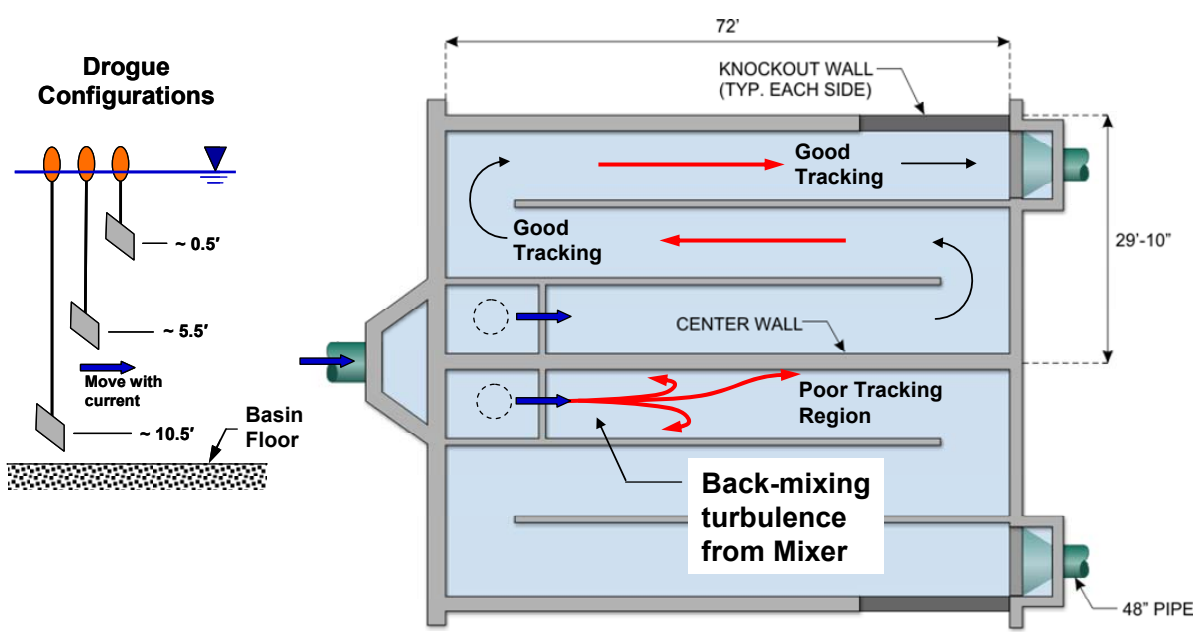
flow condition than in the low flow condition. In the high flow condition, the first tracer is detected at about 0.6 of the theoretical HRT, with approximately 62% of the tracer mass passing the outlet in advance of the theoretical HRT. This leaves the remaining 38% to pass after the theoretical HRT, with the last tracer being detected at about 1.6 HRT. As with the low flow, both the peak of the tracer mass and the centroid of the dispersed tracer mass pass the outlet well in advance of the theoretical HRT. As expected, in the high flow condition, short-circuiting is the dominant characteristic of the flow regime in the channel. Similar analyses can be done for the East CCB using the companion graphs in **Appendix F**.

For all dispersion tests conducted for the low and high flow conditions on the East and West basin, the observed HRT occurred prior to the theoretical HRT for that flow. Any improvements to the basins designed to enhance the plug flow characteristic will benefit both low and high flow performance.

3.2.4 Results of Drogue Observations

As a means to more fully visualize the information contained in the dispersion analysis, the project team also conducted observations of a float, known as a "drogue," as it moved through the CCB channel. The drogues used in this study monitored flowpath at three different depths. A qualitative summary of the drogue observations is given in **Figure 3-12**.

Figure 3-12
Drogue Analysis Schematic Description



The essence of these observations is that when the drogue was placed into the channel just downstream of the outlet from the rapid mix chamber, it found its way to the side walls of the channel's first pass and often stopped, and in some trials the drogue actually reversed direction and moved together near the wall

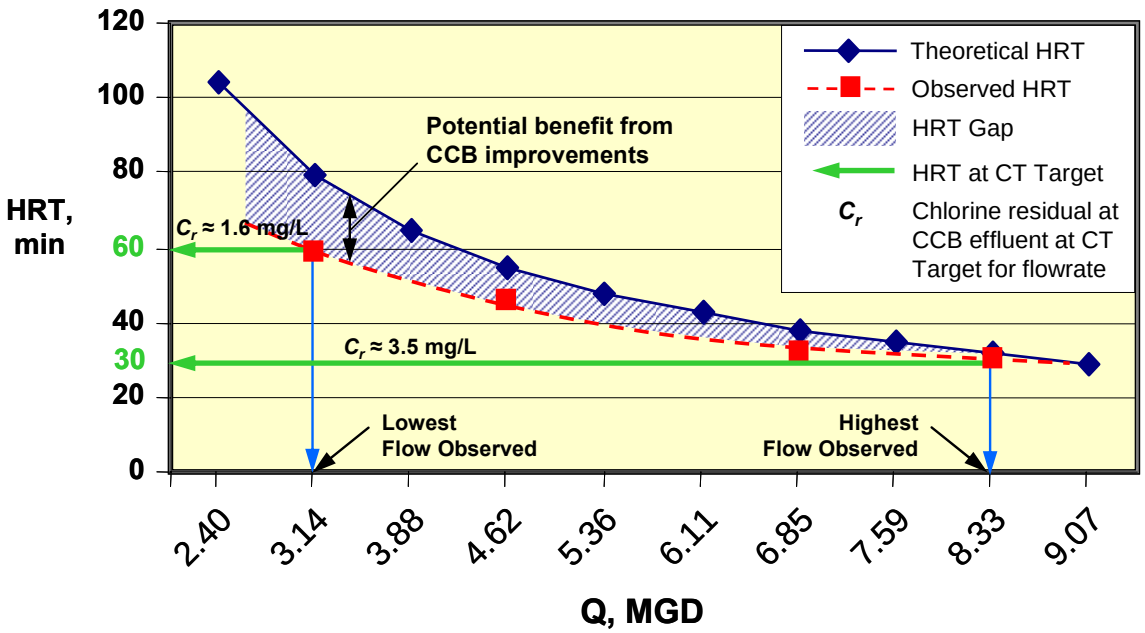
before stopping. In the second and third passes, the drogues tracked the longitudinal flow path reasonably well. These observations confirm the suspicion that the turbulence created by the vertical mixers in the flash mix chambers do result in some back-mixing of the channel flow in the first pass. But beyond the first pass, this problem seems to dissipate (at least as far as surface flow patterns are concerned). It appears that the first "end-turn" of the serpentine channel attenuates the majority of the turbulent energy induced by the mixer. The implication here is that if improvements to the channel to reduce back-mixing conditions are contemplated, the emphasis should be on the first pass in the serpentine flow.

3.2.4.1 Relationship of Channel Hydraulics to Disinfection

The intent of the above field study results was to establish a relationship between the actual CCB contact time that results from the existing system hydraulics to that which the kinetic studies found was necessary to meet the disinfection requirements of the BADCT. To do this, we return to the differences between theoretical and observed HRT and superimpose the target CT.

In **Figure 3-13** the relationship between the theoretical and observed HRT is plotted for the range of flows observed during the tests. As previously pointed out, there is an overall characteristic of short-circuiting in the CCB causing there to be a "gap" between the observed and the theoretical. This gap indicates the degree of improvement necessary to reach optimal performance for any given flow. This gap increases as flows decrease. Therefore, CCB improvements would mostly benefit the system when operating under lower flow conditions. It should be noted that this information does not reflect any additional contact time that may be provided in the 48-inch effluent discharge conduit that conveys the CCB effluent to the point of dechlorination. This additional contact time is likely in the range of 5 minutes.

Figure 3-13
Relationship of Observed to Theoretical HRT to CT



A CT target of 85 mg/L*minutes (Section 3.1.2) for the enhanced system is the minimum predicted by the kinetic model for reliable compliance with the single sample maximum criterion. But this CT projection (85 mg/L*minutes) in the bench-scale was based on samples held in a "batch" mode for each contact time studied. These batches simulate a perfect plug flow condition, and thus equal to the theoretical. Because of this, and other uncertainties in conditions deriving the model, the recommended target CT for the basis of design for improvements is a minimum of 100 mg/L*minutes at maximum flow conditions. Standard procedure for the current operation of the BNRAS disinfection process is a NaOCl dose in the range of 1.2 to 1.5 mg/L. In order to sustain the CT of 100 mg/L*minutes in the enhanced process, a chlorine *residual* concentration at the CCB effluent needs to range from 1.6 to 3.5 mg/L to meet this CT target for the range of flows observed in this test.

These residual concentrations indicate that application dosages of the NaOCl of at least twice, perhaps three times, greater depending on the chlorine demand, than what is currently being applied will be necessary. For the maximum flowrate observed, the observed HRT is approximately 30 minutes, meaning that to reach a CT of 100 mg/L*minutes in the existing system, the effluent chlorine residual concentration must be approximately 3.5 mg/L. In these high flows, the importance of plug flow in the CCB is critical because the amount of exposure time to the residual is reduced. At low flowrates (where the observed HRT is about 60 minutes), a minimum chlorine residual concentration of about 1.6 mg/L is necessary to reach the CT target of 100 mg/L*minutes in the existing system. But at these low flow ranges, the CT is very sensitive to the residual concentration, and the actual dosages required will likely be higher than what might be expected. Therefore, enhancements to the CCB to improve the HRT for these conditions will be beneficial. A more "ideal" HRT reduces the sensitivity of the chlorine residual

concentration in all flow ranges. The BNRAS basis of design flow rates and respective peaking factors are listed in **Table3-2.**

Table 3-2
Design Flow Rates and Peaking Factors for Existing BNRAS Plant

Design Flows	Rates, MGD	Peaking Factors
Minimum Flow	9.0	0.72
Average Annual Flow	12.5	1.00
Maximum Monthly Flow	16.3	1.30
Peak Wet Weather Flow	23.8	1.90

It is important to also note that contact time minimums are typically a factor in the regulatory framework for CT requirements, and the definitions vary. For example, according to USEPA, the "T" in the CT is defined as that time when 10% of a tracer mass reaches the basin outlet, a value the EPA identifies as "t_{10}". In some state regulations, however, the "T" is computed as that time when the peak of the tracer mass passes the outlet, known as the "modal" contact time. From the field dispersion analyses cited in this report (Section 3.2.3), the observed modal time is approximately 90% of the relative theoretical contact time for the range of flows studied.

3.2.5 Conclusions from Mixing and Dispersion Studies

Several conclusions can be drawn from these mixing and dispersion studies of the performance of the existing BNRAS CCB that ultimately relate to BADCT compliance. In terms of mixing behavior for the existing system, these are:

- The WaterChamp™ unit mixer appears capable of providing adequate mixing in the entry chamber where the chlorine is injected.
- The position of the WaterChamp™ unit in the influent entry chamber is less than ideal and should be repositioned to optimize the mixing regime in this chamber.
- The vertical shaft flash mixers create similar mixing regimes in both the East and West basin flash mix chambers.
- The hydraulic time-to-peak behavior of the flash mix chambers is longer than what would be expected from a basis of design; this behavior is accentuated in low flow conditions.
- The hydraulic residence time in the flash mix chambers is significantly longer than the theoretical; the turbulence caused by the mixers appears to result in back-mixing; this behavior is accentuated in low flow conditions.
- The differences in times-to-peak between the East and West flash mix chambers indicate a flow imbalance between the East and West basin.

In terms of dispersion behavior of the existing system, these are:

- Deviations from ideal plug flow are evident under all flow conditions observed; deviations are most significant under low flow conditions.
- At low flow conditions, both short-circuiting and stagnation occur.
- At high flow conditions, performance is closer to ideal plug flow.

- Observed hydraulic residence times in the CCB channels are less than the respective theoretical times for all flow conditions observed; implication is that short-circuiting is occurring, even in low flow conditions.
- Enhancements to the CCB channel are necessary to improve the observed HRT to as near the theoretical as practical. This is especially beneficial for achieving the target CT during all flow conditions.
- Significant deviation from uniform flow conditions are most prevalent in the first pass of the CCB channel; condition appears directly related to back-mixing effects from the large mixers in the upstream flash mix chambers; more uniform flow is observed in second and third passes.

4. Recommendations for Improvement

Improvements to the existing BNRAS chlorination process system are necessary to enhance its performance in order to reliably meet the BADCT criteria for microbial inactivation. The improvements focus on both the mixing system that disperses the injected chlorine into the bulk fluid and in the chlorine contact basin that provide the contact time for microbial exposure to the chlorine residual. The fundamental objective of these improvements is to boost the CT of the system to the range where achieving the 4-out-of-7 days of non-detect for *E.coli* and reliably meeting the single sample maximum criterion of 15 MPN/100 ml. It is recommended that the target CT be a minimum of 100 mg/L*minutes at maximum flow conditions.

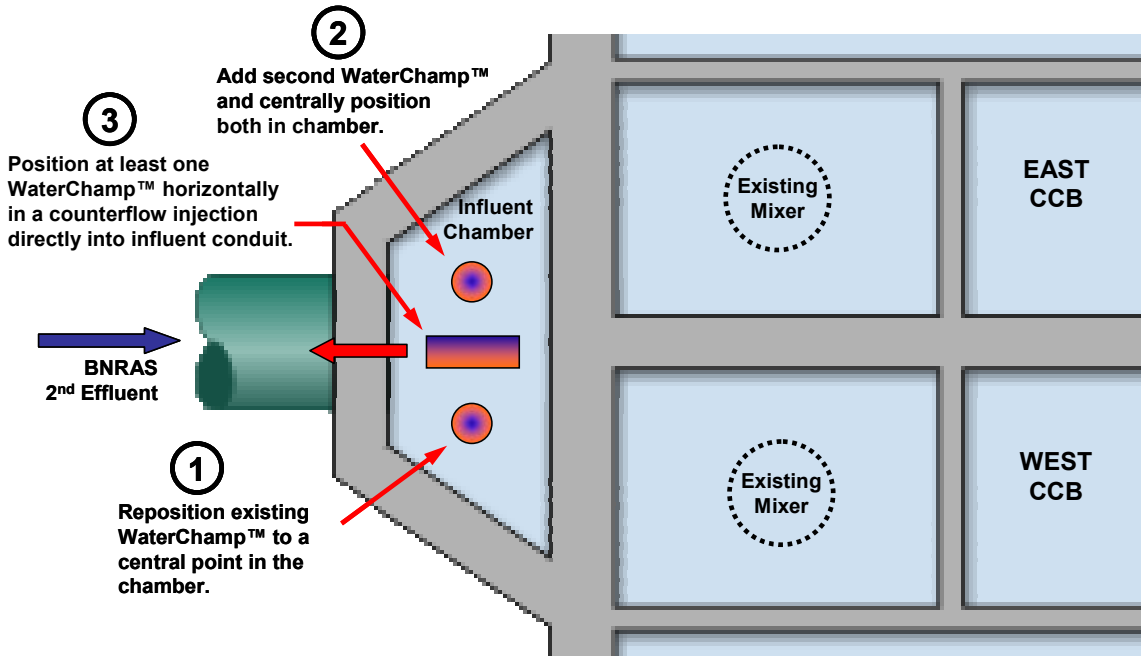
The recommendations described here for improvements to the existing BNRAS chlorination process do not include the installation of effluent filtration prior to disinfection. Therefore, it must be emphasized that reliable compliance with the single sample maximum criterion for *E.coli* depends on, and is highly sensitive to the operational performance of the upstream treatment process, especially during periods of high flows. Consistent performance of the final clarifiers in the existing BNRAS plant (and in new plants to be built in the future as part of the ROMP) to deliver a high quality secondary effluent with respect to total suspended solids will be absolutely essential. It is strongly recommended that a review of standard operating procedures for final clarification be completed to ensure that the performance consistency is being maximized. Additional information on this topic is provided in Section 4.3.

The enhanced chlorination system requires improvements to both the system's capability to deliver higher chlorine dosages, and in the CCB flow hydraulics to minimize short-circuiting, back-mixing, and stagnation zones, and create as close to plug-flow behavior as practical. The improvements to the chlorine delivery system relate to dosage; the improvements to the mixing enhance the uniformity of dispersion of the chlorine into the bulk fluid; the improvements to the channel hydraulics enhance the flow characteristics of the bulk fluid to expose the microbes to the highest possible chlorine residual for the longest possible period of time.

4.1 Mixing Improvement Recommendations

The schematic shown in **Figure 4-1** illustrates three recommendations that should result in improving the uniformity of chlorine dispersion into the BNRAS secondary effluent bulk fluid in the entry chamber of the existing chlorine contact facility.

Figure 4-1
Influent Chamber Mixing Upgrade Recommendations



The three recommendations are as follows:

- Reposition existing WaterChamp™ to a central location within the entry influent chamber. This will improve the uniformity of the dispersion of the injected chlorine throughout the bulk fluid in the influent chamber.
- Purchase a second WaterChamp™ to supplement the existing and place the two centrally within the influent chamber.
- Place one WaterChamp™ in a horizontal position, with the injector facing into the incoming flow from the BNRAS secondary in the center of the chamber to inject the chlorine as a "counterflow" to the incoming flow.

An additional point of consideration:

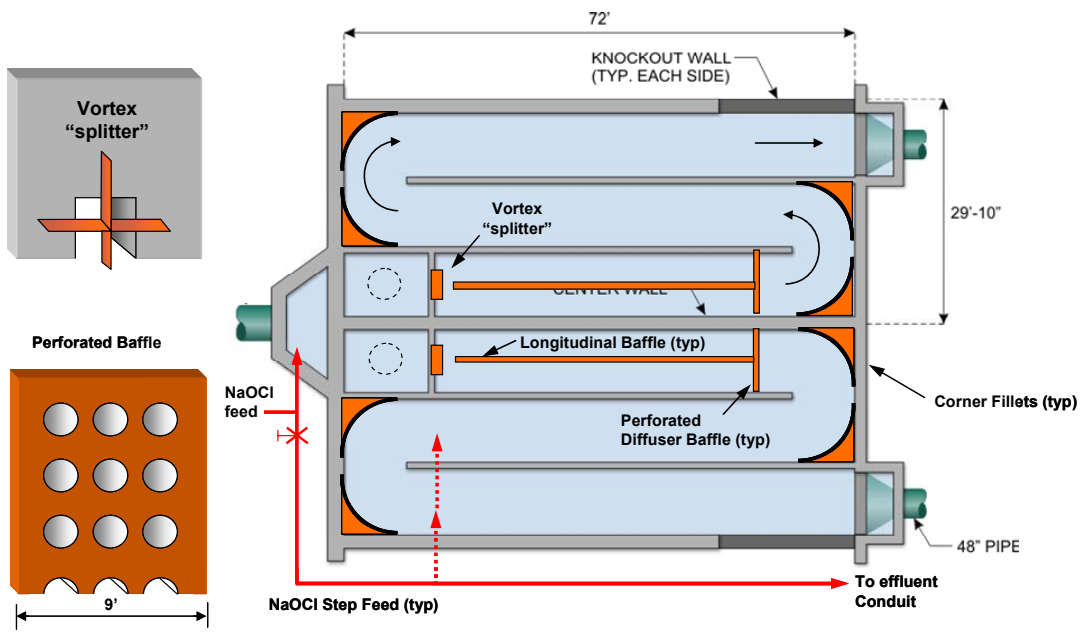
Though not evaluated in this study, consideration of the installation of a "static mixer" unit for chlorine injection in the existing BNRAS secondary effluent 60-inch conduit to replace and/or supplement the injection and mixing of the WaterChamp™ unit(s) may have merit. Because significant head loss will occur through the static mixer, a detailed hydraulic analysis must be done as part of the preliminary design. There currently exists 1.06 feet (+/-) of available hydraulic head under peak wet weather flow conditions between the final clarifier effluent channel and the CCB influent chamber. It is possible that the head loss through a static mixer could be as much as two feet, which for this application would be problematic. Also, a static mixer has the potential to trap debris that may be present in the bulk fluid

passing through it. However, this is not a highly likely scenario since the BNRAS secondary effluent should be relatively free of errant debris. Furthermore, the mixing efficiency of such a mixing unit is a function of both flow rate and water temperature. Specifically, the mixing efficiency decreases with decreasing flow rate and with decreasing water temperature. Therefore, a static mixer does not have the operational flexibility to adjust to adverse conditions such as low flow rates and cold water temperatures. It is for these uncertainties that it is also strongly recommended a pilot-scale study/test be conducted to analyze the efficiency of such a mixing unit to determine its appropriateness and applicability for this enhanced chlorination process.

4.2 Chlorine Contact Channel Improvement Recommendations

Figure 4-2 illustrates the recommendations for improvements to the existing BRNAS chlorine contact basin to improve the hydraulics of the channel flow.

Figure 4-2
Chlorine Contact Basin Upgrade Recommendations



The recommendations are as follows:

- Consider the installation of "rounding" fillets in all corners of the serpentine flow channels; creates more uniform flow around corners and minimizes potential for dead zones where stagnation can occur, especially in a low flow condition.
- Consider the installation of a perforated baffle at the end of the first pass of the serpentine channel to enhance plug flow characteristics (see illustration in FIGURE 4-2). This baffle will increase the head loss across the basin and therefore requires a detailed hydraulic profile analysis as part of its design.

- Consider ceasing operation of the vertical shaft flash mixers; these appear to be creating turbulence in the first pass of the serpentine channel, significantly disrupting plug flow in the first pass.
- If it is found that continued operation of the flash mixers is necessary, then the following features would be appropriate:
  - Consider installation of a "vortex" splitter on the outlet side of the flash mix chamber outlet orifice (see illustration in FIGURE 4-2) to reduce back-mixing caused by the vertical shaft flash mixers.
  - Consider a longitudinal baffle in the middle of the first pass running the full length of the first pass. This will enhance the uniform flow characteristic in the first pass.
- Consider the installation of a "step feed" chlorination line to allow for supplemental chlorination downstream of the initial chlorine injection point. Downstream locations should include beginning of the third pass and in the 48-inch effluent conduit.
- Periodic cleaning of the CCB is imperative for ensuring optimal performance. It is recommended that PCWMD operations and/or maintenance staff take each of the CCBs out of service at least once, preferably twice annually for cleaning. Cleaning should consist of high-pressure washing using water and/or light bleach solution on all walls and floor, orifices and weirs. Following cleaning the CCB should be filled and "shocked" with up to 50 mg/L of chlorine and held for at least 24 hours prior to discharge and return to full operation.

4.3 Recommendations for Additional Studies on Existing BNRAS Disinfection System

The scope of this Phase II study did not allow for consideration of the full range of issues that should be examined for evaluating enhanced chlorination as an effective and reliable disinfection process for meeting the BADCT standards. Therefore, the following are suggestions for additional studies that PCWMD should consider to supplement the information in this report.

- Operational data during the kinetics studies reported herein indicate the pH of the BNRAS secondary effluent is above 7. With enhanced chlorination practice, the pH in the CCB will likely increase slightly after sodium hypochlorite is added at the elevated doses. Slight downward adjustments in the pH (perhaps 0.2 to 0.4 units) would provide significant benefit to the effectiveness of the chlorination process (increases the concentration of HOCl which is more powerful than OCl^-). Such an adjustment would still be well within permit limitations for pH of the final effluent. It is recommended that PCWMD closely monitor the pH in the CCB to determine whether pH adjustment is worth considering as a tool to supplement the enhanced chlorination performance. If the results are favorable for such an adjustment, simple bench-scale (jar test) studies using H_2SO_4 and/or HCl would be warranted to determine if this benefit can be achieved economically. This increase in disinfection efficacy provides PCWMD with an addition margin of protection against primarily the single sample maximum criterion. These tests can be readily conducted in PCWMD laboratory by PCWMD analytical staff. It must be noted, however, that the formation of disinfection by-products remains and issue for consideration (discussed later).

- The enhanced chlorination process requires close monitoring of the correlations between chlorine residual at the end of the contact period. Operationally, this translates to rigorous attention to the initial chlorine dose. It is strongly recommended that PCWMD analytical staff conduct a series of

bench-scale (jar test) studies that correlate chlorine dose to residual as a function of contact time. Such tests will establish chlorine dosage (lower and upper) that will serve as the "boundaries" for planning the operational procedures for the enhanced system. These studies will also serve to provide PCWMD with information necessary to project annual chlorine usage to support budget planning and frequency of chemical deliveries.

- In conjunction with the above bench-scale testing on chlorine dose, it is recommended that PCWMD analytical and operations staff proceed with the originally proposed field tests to analyze the rate of chlorine residual decay in the full-scale BNRAS chlorine contact basin. These residual decay rate studies should be conducted over at least two depths in the channel to ascertain the influence of temperature and light on chlorine breakdown in the upper surface layers of the flow in comparison with the same at depths near the channel floor. These studies should be conducted under both summer and winter months to take into account the difference in chlorine decay rate at different water temperatures.

- The enhanced chlorination process will likely mean operating at higher dosages of chlorine than what has been standard practice at the existing BNRAS facility. Depending on the type and concentration of organics that remain in the treated BNRAS secondary effluent, various disinfection by-products can form as a result of reacting with the chlorine. The presence of these disinfection by-products in the final effluent has ramifications for water quality issues surrounding the water's ultimate reuse. It is therefore strongly recommended that PCWMD conduct a disinfection by-product formation potential (DBPFP) test, which is a series of bench-scale (jar test) studies that analyze the types and concentrations of disinfection by-products that are likely to form as a result of the enhanced chlorine dosages that will be applied. The test should include warm water conditions because this is typically a "worse case" condition (generates the highest DBP formation potential). Furthermore, if it is determined that pH reduction will be useful in enhancing the disinfection efficiency, then the impacts of pH on DBPFP should be investigated since formation of most DBPs is a function of pH. For example, the formation of trihalomethanes generally decreases with decreasing pH while the formation of haloacetic acids generally increases with decreasing pH.

- Due to the potentially higher chlorine dosages that will likely be necessary to support the enhanced chlorination process, it is recommended that PCWMD evaluate the sizes of their existing sodium hypochlorite storage and feed facilities to assess whether the existing facilities are adequate to accommodate this increase in chlorine dosage (these rates could be as much as three times the current dosage rate).

- The enhanced chlorination process will likely also mean operating the dechlorination process at higher doses to ensure compliance with the AZPDES permit for chlorine residual in the final discharge. (Similar to the above statement, it is recommended that PCWMD evaluate the sizes of the existing storage and feed facilities for the sodium bisulfite dechlorination agent to ensure its capacities are adequate to support the requirements of the enhanced chlorination process.) It will also be important to determine if higher doses of the dechlorinating agent pose threat to aquatic toxicity, since this may impact compliance with the Whole Effluent Toxicity (WET) biomonitoring tests. It is therefore strongly recommended that the PCMWD conduct a set of bench-scale (jar test) studies to assess the potential for excessive dechlorination agent

concentrations to create effluent toxicity issues. If the PCMWD plans to consider alternative dechlorination agents, these studies should include assessment of required dose and reaction time, the toxicity properties of the dechlorinated effluent and other potential water quality impacts the alternative dechlorination agents may create.

- One of the most critical operational factors influencing the reliability of performance of the enhanced chlorination process is the control of total suspended solids in the BNRAS secondary effluent. As noted previously, the TSS concentrations during the kinetics analyses were at or below 5 mg/L, signifying excellent performance of the BNRAS final clarifiers. Even at this low level of TSS, the bench-scale kinetic testing conducted in this study exhibits a "tailing" effect, which is at least partially caused by particle shielding. In high flow conditions during a wet weather event or during performance upset events, for example, it is probable that the concentration of TSS in the secondary effluent could be much higher than 5 mg/L. Increases in TSS can jeopardize compliance with the single sample maximum, and, if these conditions persist for consecutive days, it could jeopardize compliance with the 4-day ND requirement. It is imperative that operation of the final clarifiers be monitored continuously.

  Therefore, two recommendations are hereby posed with respect to final clarifier operations. First, it is recommended that PCWMD conduct an exhaustive and critical review of its standard procedures for operating the existing BNRAS final clarifiers under average and peak flow conditions. These procedures should be reviewed within the context of available historical operational data. Correlations of the effluent suspended solids concentrations to flow rate should be established from the record. If the data exists, a correlation between Solids Volume Index (SVI) and effluent suspended solids concentrations should be established. Using these correlations, modifications to the operational procedures should be made, if necessary, to ensure optimal performance of the clarifiers.

  Secondly, it is recommended that PCWMD operations staff develop and utilize a State Point Analysis (SPA) protocol for operating the existing BNRAS final clarifiers. This procedure provides the facility operators a proactive approach to clarifier operation because it integrates the sludge settling characteristics with both the plant flow condition and the rate of sludge removal via the underflow. The SPA provides the operator with performance information in real time, allowing the operator the "see" the performance limits before they are exceeded and make the appropriate process control decisions to keep within the limits. The SPA protocol can be developed and implemented with PCWMD resources and staff.

  Finally, it goes without saying that the performance of the biological treatment process in the existing nitrogen removal treatment process train influences the performance of the final clarification process. Upsets in treatment performance can result in the proliferation of filamentous organisms that can cause poor settling of the biomass in the clarifiers. Poor settling can result in solids carryover to the chlorine contact basin, reducing the effectiveness of the chlorine. Similarly, treatment upsets that result in the inhibition of complete nitrification can pass "high" levels of nitrite or ammonia on to the chlorination system, which again, reduces the effectiveness of the chorine. Therefore, it is highly recommended that an exhaustive and critical review of the existing BNRAS treatment process control procedures be conducted within the

context of process upsets. Modifications should be made to the process control Standard Operating Procedures, as necessary, to ensure optimal performance is consistent.

- It is recommended that PCWMD staff review its current sample locations for effluent *E.coli* and chlorine residual compliance monitoring and reporting for the existing BNRAS facility. It is possible that a more optimal location exists that is more representative of the true BNRAS chlorine disinfection system performance. This also may mean that monitoring stations be established for both the BNRAS plant and the HPO plant along with the final discharge compliance point in order to isolate the differences between the two facilities.

4.4 Basis of Design Recommendations for Enhanced Chlorination Disinfection Systems for Future BNRAS (Bardenpho) Facilities

Results of the studies and analysis discussed in this report provides information for the basis of design that should be applied to the enhanced chlorination process at future wastewater treatment facilities within PCWMD service area jurisdiction. These include:

1. Minimum CT applied under maximum flow conditions should be 100 mg/L*minutes and applied to the inactivation of the target organism: *E.coli*. This value will of course need to be reevaluated if, in the future, the State of Arizona promulgates new disinfection regulations related to microbial inactivations.

2. Chlorine contact basin should be constructed with a length-to-width ratio of no less than 20:1.

3. Chlorine injection and initial mixing should incorporate the recommendations outlined in Section 4.1. The critical element of these is the application of the WaterChamp™ unit as the initial chlorine injection and mixing apparatus. Its position in the influent chamber is critical to the optimization of the initial mixing to achieve uniform distribution of the chlorine throughout the chamber. This can be accomplished by using:

   - Two units, oriented vertically in the chamber and in such manner as to divide the chamber equally into two volumes, or
   - One unit, oriented horizontally in the center of the conduit conveying the secondary effluent flow into the chamber, with the injection being counterflow to the influent flow.

   An advantage of the first option is system redundancy.

4. Chlorine contact basin for the existing BNRAS process should incorporate the recommendations outlined in Section 4.2. The essential elements include:

   - Rounding of the square corners with a constant radius fillet at the end of each of the serpentine passes using materials consistent with the contact basin wall construction materials;
   - Installing a longitudinal baffle wall in the center of the first pass, beginning immediately downstream of the outlet from the mixing chamber, continuing for the length of the first pass and ending at the start of the end fillet;

- Consideration of ceasing the operation of the vertical shaft mixer units because of the degree of back-mixing and disruptions of plug flow that these tend to create.
- If vertical shaft mixers are utilized in the flash mix chamber, consider installing a vortex splitter device on the downstream side of the outlet orifice of the flash mix chamber to reduce back-mixing;
- If hydraulic head permits, install a perforated baffle wall at the downstream end of the first pass to promote uniform flow (particularly necessary if vertical mixers are specified for the flash mix chamber; and
- Providing for step feed of NaOCl to points downstream in the chlorine contact basin (including points in the conduit conveying basin effluent to the dechlorination chamber) as a means to boost chlorine residuals during critical flow conditions.

5. Construct chlorine contact basins for expandability if increases in CT are necessary to comply with future disinfection regulations promulgated by the State of Arizona.

6. Contact time in the chlorine contact basin should be not less than 30 minutes in average daily flow conditions, and not less than 20 minutes in peak flow conditions.

7. Storage and feed facilities for sodium hypochlorite should be sized based on the dose needed to achieve the target CT (100 mg/L*min) at the residence time recommended above. These facilities should be also constructed for expandability if increases in CT are necessary for future disinfection regulations promulgated by the State of Arizona.

8. Surface overflow rate (SOR) for the final clarifier design should not exceed 400 gpd/ft^2 for average flow conditions, and 600 gpd/ft^2 for peak conditions. The driving force behind these recommended values is providing the margin of protection against violation of the single sample maximum criterion for *E.coli*. It is to be noted that this "margin" is intended to provide protection against noncompliance during very small percentage of time in a given year where a severe wet weather event or some unforeseen operational anomaly results in high suspended solids concentrations in the secondary effluent. But, the increased final clarification capacity generated by these target design overflow rate values does have economic consequences. Therefore, PCWMD is strongly encouraged to carefully evaluate the standard operating procedures currently in place for responding to such abnormal conditions. Revisions to these operational strategies to maximize control of solids in the secondary effluent (including approaches such as the State Point Analysis as discussed in Section 4.3 above) can help to reduce amount of added clarifier capacity required, thereby minimizing the economic impacts.

9. An on-line turbidity meter should be considered for monitoring particulate concentrations in the treated secondary effluent prior to the disinfection process. This monitoring system would serve as an on-line "alarming" device to inform operations personnel of changes occurring in the effluent water quality in advance to allow time for corrections and/or adjustments in operational changes.

10. On an annual basis clean and inspect the chlorine contact basins. Basin cleaning removes solids buildup in the system which may under high flow conditions carryover and impact disinfection performance.