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UNITED STATES AGENCY FOR
INTERNATIONAL DEVELOPMENT
(USAID / JORDAN)

**GREATER AMMAN WATER PROBLEMS
JULY-AUGUST 1998**

**ZAI WATER TREATMENT PLANT ASSESSMENT
FINAL REPORT (Revised)**

JANUARY 1999

USAID IQC CONTRACT LAG-I-00-98-00034-00
USAID TASK ORDER # 800
CAMP DRESSER & McKEE INTERNATIONAL INC (CDM)
AMMAN, JORDAN

CDM gratefully acknowledges the contributions of
Mr Robert Monk and Mr Dave Ogden
in preparation of this document

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ABBREVIATIONS

a	Annum
AWWA	American Water Works Association
ASCE	American Society of Civil Engineers
BFV	Butterfly valve
C	Disinfectant concentration or Celsius
CDM	Camp Dresser & McKee International Inc
Cl ₂	Chlorine
ClO ₂	Chlorine dioxide
CT	The product of average concentration of disinfectant and time of contact
DBP	Disinfectant By-Product
FPA	Flavor profile analysis
GAC	Granular activated carbon
hr	Hour
JICA	Japan International Cooperation Agency
IPS	Intake Pump Station
KAC	King Abdullah Canal
Kg/cm ²	Kilograms per square centimeter
km	Kilometers
KMnO ₂	Potassium permanganate
L/min	Liters per minute
L/min/m ²	Liters per minute per square meter
m	Meters
ml	Milliliter
m/min	Meters per minute
m/s	Meters per second
min	Minute
mm	Millimeters
m ²	Square meters
m ³	Cubic meters
m ³ /d	Cubic meters/day
m ³ /d/m	Cubic meters per day per meter
m ³ /d/m ²	Cubic meters per day per square meter
m ³ /min	Cubic meters per minute
mg/L	Milligrams per liter
Mm ³ /a	Million cubic meters per annum
MCL	Maximum Contaminant Level
MIB	2-Methyl-isoborneol
NTU	Nephelometric turbidity unit
PAC	Powdered activated carbon

Abbreviations continued on next page

Abbreviations - continued

ppb	Parts per billion
ppm	Parts per million
PS	Pump station
s	Second
RW	Raw water
THM	Trihalomethane
THMFP	Trihalomethane formation potential
TOC	Total organic carbon
TON	Threshold odor number
USAID	United States Agency for International Development
USEPA	United States Environmental Protection Agency
WTP	Water treatment plant (always the Zai WTP)

CDM stands behind the recommendations provided in this report for improving the operation of the Zai Water Treatment Plant and providing the means for plant staff to respond quickly and effectively to changes in raw water quality. Each recommendation has its basis in sound engineering judgment and the concepts behind each have been applied successfully in other locations.

While CDM cannot guarantee that taste, odor, and nematode problems will never occur again, it does believe that its recommendations, along with proper plant operation and maintenance, provide the most effective and economical way of equipping the Zai plant to handle taste, odor, and nematode problems.

USAID/JORDAN

GREATER AMMAN WATER PROBLEMS, JULY-AUGUST 1998 ZAI WATER TREATMENT PLANT ASSESSMENT

FINAL REPORT (Revised)

January 1999

Executive Summary

This report has been prepared by Camp Dresser & McKee International Inc (CDM) for the United States Agency for International Development (USAID) and the Ministry of Water and Irrigation/Water Authority of Jordan, with USAID funding. Following severe taste and odor events in the water supply in July and August of 1998, CDM was asked to make recommendations to modify the plant and operating procedures to prevent a repeat of the taste and odor events, based on the following study of the Deir Alla-Zai WTP System, review of water quality and operating reports, and study of other reports and designs. The list of references used in this report is included in Appendix A. The full scope of work undertaken by CDM is given in Appendix B. Plans are in progress to double the capacity of the current conveyance, treatment, and deliverance systems through German and Japanese funding agencies.

The Draft Report of 30 September, 1998, made recommendations that some bench-scale tests be performed to better refine the final recommendations. This Final Report includes the results of these tests (Appendix C) and these are reflected in many of the findings in the recommendations herein. In addition, this report includes complete cost estimates for each of the recommendations.

The Zai Water Treatment Plant (Zai WTP), its associated intake system, raw water conveyance system, and treated water conveyance system were constructed in the 1980s. Up until July, 1998, the plant had performed well. Any dissolved odorous compounds in the water were removed through the treatment processes. However, the July-August events were so severe the plant could not, at full production rate, eliminate the taste and odor experienced. Investigation of the problem was performed by Jordanian Government Agencies, the World Health Organization, and private consultants. Two conclusions were reached: first, that the taste and odor were coming from taste and odor producing algae, second, that dead nematodes were occasionally passing through the plant. As a result, it was thought prudent to issue a boil water order.

The current system takes water from the King Abdullah Canal (KAC). The KAC serves as an irrigation canal and raw water source for the Zai WTP. The water sources for the canal are

Lake Tiberias, the Yarmouk River, the Mukheiba Wells, and, occasionally, the Wadi Al-Arab Dam. The length of the KAC, from its start to the draw-off point at Deir Alla, is approximately 65 km. It is an open canal. Water is taken from the KAC, screened, and pumped at five pump stations in series through five stretches of pipeline. Water travels vertically through approximately 1,123 meter (m) and horizontally through 14 kilometers (km).

The Za1 WTP is designed to provide a variety of treatment processes. The process train includes a flow regulating or balancing reservoir, chemical rapid mixing, flocculation, sedimentation, and filtration. Chemicals used are potassium permanganate as a pre oxidant, powdered activated carbon (PAC) for taste and odor control, alum for coagulation and particle flocculation, two polyelectrolytes to aid in coagulation and flocculation, and chlorine for disinfection. Treated water passes into a clearwell and is pumped from there to the Dabouq Reservoir. From there the water gravitates into the western part of Amman's distribution system.

The reported ranges of raw water quality parameters are not extreme when compared to the normal raw water parameters, and are easily treatable with the existing facilities. These parameters are turbidity, color, fecal coliform, algae, pH, hardness, alkalinity, and total organic carbon. The water does contain nutrients that promote algae, including those species that can cause taste and odor. The raw water also contains nematodes. The treated water records show that up until July, 1998, the Za1 WTP was treating the water effectively, meeting the Jordan Standard Specification 286/1997 for potable water. To predict a taste and odor event is very difficult. The magnitude of the July-August event was unexpected and extreme in comparison with any events experienced before. It took plant management and operating staff by surprise. Further, the one chemical available at the plant to control taste and odor had insufficient feeder capacity to meet the high demand experienced.

It can be expected that the raw water quality will deteriorate somewhat in the future because of continued development in the catchment areas. It will be necessary for all those responsible for control in these areas to enforce regulations to minimize this decline in water quality. However, the decrease in future water quality is not anticipated to warrant any major changes to the treatment processes at the Za1 WTP beyond the recommendations in this report. It is more likely that changes in treated water quality standards may necessitate a change in the current disinfectant at the plant.

The cause of the taste and odor in the treated water experienced in July and August was due to an algae bloom in the KAC of the species that primarily causes taste and odor. The detention time in the KAC is long, and, given the correct combinations, algae blooms are inevitable. The correct ratio of nutrients, water temperature, sunlight, and sufficient detention time will cause a bloom. The Za1 WTP did not have the PAC feeder capacity to handle such an event. The feeder capacity of the duty and standby feeders was only 10 mg/L each. Tests performed by a German specialist at the time demonstrated that at least 60 mg/L was needed.

The exact sources of the dead nematodes identified in the water during the intense investigations in July and August have not yet been determined. They may originate from any or all of the raw water sources or may be entering the canal with stormwater run off.

from adjoining agricultural lands. In any event, it is likely the nematodes are breeding in the bottom deposits of the slow flowing KAC. If the filter media at the plant are not effectively cleaned, then the media can harbor nematode breeding sites, as well.

CDM, after studying all available information, has identified a number of modifications and additions to the overall system that will minimize the possibility of another taste and odor event occurring again, while controlling nematodes more effectively. Many of the recommendations in this report are endorsements of suggestions made by others who have studied this problem. Included also are comments where CDM may not agree with the recommendation of others, in some cases, it is felt the recommendation may exacerbate the problem, instead of alleviate it.

- CDM recommends that the PAC application point be relocated to the vault on the raw water line just upstream of the regulating reservoir. This will allow a longer time for the carbon to adsorb taste and odor and organic compounds, and its effectiveness will not be minimized by the coagulant floc. To limit short-circuiting in the regulating reservoir, CDM is recommending that this reservoir be baffled and the two compartments operated in parallel. The bench-scale tests demonstrated the benefits of this recommendation.
- CDM recommends the use of ferric sulfate for coagulation instead of the alum currently used. Ferric sulfate will be a more optimum coagulant than alum at the normal raw water pH levels experienced. This change will also avoid the use of an acid with the alum. The test results and cost analyses show ferric sulfate to be the better iron salt.
- CDM recommends the powdered activated carbon feeders and slurry pumps be increased in capacity to 35 mg/L each at full plant capacity as recommended in the German report. When all the other recommended modifications are implemented, CDM does not believe feeding at this high of a rate will be necessary.
- CDM recommends that the relocation of the application of potassium permanganate to the raw water from the present inlet, the plant's regulating reservoir, to the Intake Pump Station. Currently, copper sulfate is being added there at the suggestion of one of the reviewing consultants. CDM believes the potassium permanganate will do just as effective a job of inactivating the algae and will also aid in the inactivation of nematodes, particularly when used together with chlorine dioxide.
- CDM recommends adding chlorine dioxide to the raw water at the Intake Pump Station as the primary disinfectant and to aid in taste and odor and nematode control.
- CDM recommends that the existing mechanical electric motor-driven rapid mixers for the coagulant chemical and coagulant aid be converted to hydraulic flash mixing, utilizing available head at the plant and thereby creating savings in electrical and chemical costs.
- CDM recommends adding a perforated inlet wall to the flocculation basin to reduce short-circuiting in the first stage and to improve flocculation, and to make permanent the application points for flocculant polymer aid at all second and third stage flocculators.

-
- CDM recommends the addition of perforated outlet walls in the sedimentation basins and the abandonment of the finger weirs and troughs. This will improve the basins' effectiveness in removing fine floc and minimize carryover on to the filters.
 - CDM recommends that the filter operation and controls be modified to allow for the elimination of the initial turbidity spikes immediately following start-up after backwashing.
 - CDM recommends the use of a filter aid polymer to help in the performance of the filters and in the effective removal of dead nematodes. CDM does not recommend adding PAC to the settled water.
 - CDM recommends that the existing filter surface wash water system be replaced with an air scour method for full-depth filter media cleaning. CDM further recommends the blowers and controls for the air scour system be part of the Japanese design.
 - CDM recommends the constant speed wash water recovery pumps be converted to variable speed. These pumps are believed to be replaced with larger pumps under the proposed Japanese expansion design, however, this may be unnecessary if the existing filter surface wash system is replaced with an air scour system, as recommended herein.
 - CDM recommends that the piping at the storage (flow balancing) tanks at four of the raw water pump stations be modified, and new piping added, to allow water to pass through them and avoid stagnation and algae growth. CDM also recommends the tanks be baffled to avoid short-circuiting.
 - CDM does not agree with the addition of ferric chloride at the proposed settling basins at the Intake Pump Station site. These basins are designed to settle out the silt in the water and reduce wear on the pump impellers. These basins would only be cleaned out occasionally. Adding ferric chloride will precipitate out a great deal of organic matter. This will decompose and could create further taste and odor problems. The removal of organic particles in the water is better left to the existing plant's sedimentation basins where the deposited sludge is vacuumed off the floor regularly and therefore, will not contribute to taste and odor.
 - CDM does not recommend adding ferric chloride to the raw water at the head of the KAC to precipitate out phosphorous, one of the nutrients that algae depend upon. This chemical coagulant will precipitate out more than phosphorous, thereby increasing bottom deposits. These deposits will add to the algae taste and odor problems when these bottom deposits are resuspended. Consideration should be given to using an algicide as an alternative.
 - CDM does not recommend that the existing filter media be replaced with granular activated carbon (GAC) over a shallow layer of garnet at this time.

Each recommendation has its basis in sound engineering judgment. In addition, the concepts behind the recommendations have been successfully applied at other plants in the US and

Europe. These include recommendations for the use of chlorine dioxide and potassium permanganate as oxidants, PAC contact basins, hydraulic flash mixing plates, perforated inlets and outlets (no finger weirs) in the rectangular sediment basins, ferric sulfate as a coagulant, filter aid polymer, filter air scour systems, and tank baffling.

CDM cannot provide an outright guarantee that taste, odor, and nematode problems will be prevented 100 percent of the time. However, CDM believes that, along with proper plant operation and maintenance, its recommendations provide the most effective and economical way of equipping the Zai plant to handle taste, odor, and nematode problems.

In viewing the Japanese report on the proposed Zai WTP duplication, CDM recommends the design as proposed be amended to incorporate the CDM recommendations to the existing plant, as stated above and in more detail in the body of the report. The Japanese proposed instrumentation and control system should include updating and integrating the existing plant control system. It is important that the two plants be identical in design, perform in the same manner, and be controlled as one plant from a central control room.

The Japanese design should also include a coagulant polymer aid and ensure that the PAC feeder system be capable of dosing at up to a total of 70 mg/L at full plant capacity. This PAC system should also include conveyor loaders, bag splitters, compactors, and dust extractors. The recommendations of the German report have, for the most part, been agreed to.

The matrix which follows provides a summary of CDM's recommendations, in priority order, as well as expected benefits, approximate costs, and other comments concerning each recommendation. Note that the cost estimates provided are "planning level" estimates only and will be developed and revised during design for the complete program.

SUMMARY OF RECOMMENDATIONS FOR THE ZAI WATER TREATMENT PLANT

No	Description of Recommendation	Benefits	Cost (JD)	Comments
1	Relocate the PAC application point to the chemical injection vault on the raw water pipeline before the regulating reservoir Relocate the chlorine application point from this vault to the settled water channel before the filters	(a) Improves taste & odor control while reducing necessary dosages (b) more effectively reduces THM precursors	0	Chlorine must be relocated concurrently with the PAC relocation
2	Convert from alum to ferric sulfate as the primary coagulant	(a) Provides a heavier floc to maximize nematode removal in the sedimentation basins, (b) eliminates the need to adjust pH in the raw or treated waters with acids and bases, (c) eliminates the immediate need to upsize the existing alum feeders, (d) improved flocculation reduces load on filters (e) forms less sludge than alum which also dries more readily (f) overall operating cost comparable to that of alum system (with pH adjustment)	0	Polymer testing should be conducted to ensure the use of one with the greatest compatibility and effectiveness with ferric sulfate
3	Replace the existing PAC feeders and slurry feed pumps with new feeders and pumps to allow feeding PAC at 35 mg/L capacity each at a plant flow of 246 000 m ³ /d	(a) Increases the plant's ability to adequately handle taste & odor problems of the magnitude of the 1998 event and larger	200 000	Cost estimate includes capacity for existing and expanded plant requirements
4	Add a potassium permanganate feeding system at the Intake Pump Station	(a) Increases the contact time and therefore the effectiveness of KMnO ₄ as an oxidant for controlling taste & odor and nematode inactivation	85,000	Cost estimate includes capacity for existing and expanded plant requirements, with building
5	Baffle the regulating reservoir at the Zai WTP	(a) Minimizes short-circuiting, (b) increases chemical contact time (c) reduces PAC dosages needed to control taste & odor	40 000	Modifications can be accomplished quickly with minimal effect on plant operation
6	Add chlorine dioxide dosing facilities at the Intake Pump Station	(a) Inactivates algae, (b) maintains clean pipeline (c) oxidizes taste & odor compounds (d) helps inactivate nematodes (e) reduces final chlorine dose needed to maintain a residual in the treated water (f) greatly reduces THM formation potential in comparison to chlorine	650 000	Cost estimate includes capacity for existing and expanded plant requirements with building
7	Change over the existing mechanical flash mixing system to a hydraulic flash mixing system	(a) Reduces flocculant chemical dosages, (b) eliminates cost of operating and maintaining the existing mechanical mixers	10 000	Elimination of mechanical mixers would provide a net cost saving in the Japanese expansion design Modifications would require minimal plant downtime

No	Description of Recommendation	Benefits	Cost JD	Comments
8	Add perforated inlet walls to the flocculation basins, change the motor drives for flocculators to their low speed, and apply polymer at impellers	(a) Creates larger floc for higher percent removal in the sedimentation basins, (b) eliminates "dead" zones in the basins to maximize settling time and space	5000	In combination with Recommendation 9 below, will require approximately 12 to 20 days of downtime for each process train
9	Add perforated outlet walls to the sedimentation basins	(a) Increases percent floc removal	15,000	Elimination of the finger weirs would provide a net cost saving in the Japanese expansion design. In combination with Recommendation 8 above, will require approximately 12 to 20 days of downtime for each process train
10	Modify the filters to eliminate the turbidity spike after backwashing	(a) Minimizes particles passing through the filters following backwashing particularly those of nematode size	88,000	Proposed modifications allow for a gradual backwash startup, filter "rest" period following backwashing the ability to add polymer during the last few minutes of the backwash cycle, and automation of backwash control
11	Add a filter aid polymer system	(a) Flocculates particles passing through the sedimentation basins to retain them on the filters and prevent their passing through	90 000	An anionic polymer is recommended
12	Provide an air scour cleaning system for the filters	In combination with backwashing, (a) provides complete filter cleaning, (b) prevents the possibility of nematodes breeding in the filter media	450,000	The cost for a duty and standby air blower, which is included in the estimate above, is sufficient to cover the existing and expanded plant needs since only one filter will be backwashed at a time. Other costs associated with the expanded plant, however (piping, etc), are not included in this estimate. It is expected that the additional (non-blower) costs of the air scour system for the expanded plant will be roughly equivalent to the related costs of the surface wash system currently proposed in that design. Air scour grid systems are marketed which allow for their installation without filter downtime
13	Convert fixed-speed recovery pumps to variable speed	(a) Ensures that recycled waste backwash water is fed to the head of the plant at a steady rate over 24 hours, rather than in slugs to help any nematodes in the waste backwash water to settle out in the sed basins	25,000	Recommendation could provide a net cost saving in the Japanese design, since the proposed larger pumps may not be required if a filter air scour system is adopted
14	Modify the piping at the storage tanks of Pump Stations 2, 3, and 4	In combination with Recommendation 15 below (a) Prevents stagnation of water in the storage tanks to prevent algae growth, (b) eliminates need to occasionally overflow the tanks to flush them out	220 000	Recommendation does away with the need to "dispose" of any water. Should be implemented after completion of the proposed settling basins at Pump Station No 1

No	Description of Recommendation	Benefits	Cost JD	Comments
15	Add baffles in the storage tanks at Pump Stations 1, 2, 3 and 4	In combination with Recommendation 14 above, (a) Prevents stagnation of water in storage tanks to prevent algae growth, (c) eliminates need to occasionally overflow the tanks to flush them out	35 000	Recommendation does away with the need to dispose of any water. Should be implemented after completion of the proposed settling basins at Pump Station No 1

10 Introduction

This report has been prepared by Camp Dresser & McKee International Inc (CDM) at the request of the United States Agency for International Development (USAID) through CDM's Indefinite Quantities Contract with USAID. In preparing for the writing of this report, CDM personnel visited the Zar Water Treatment Plant (Zar WTP) and its associated raw and treated water conveyance systems, reviewed water quality and operating records, studied available water conveyance and Zar WTP drawings, and reviewed various investigative reports related to the water quality problems experienced throughout the western parts of the city of Amman's water distribution area. CDM personnel also reviewed proposed modifications and additions to the facilities. All reference materials are cited in Appendix A of this report.

The scope of CDM's services for this report included reviewing water quality data, plant operational records, associated reports, water treatment processes, chemical requirements and dosages, operational efficiency, and projected future modifications and expansions. CDM's scope of work was limited to the conveyance and treatment systems from the King Abdullah Canal (KAC) intake at Deir Alla through the Zar WTP discharges. CDM was asked to identify modifications to the Zar WTP that would be necessary to improve water quality and reliability, considering present and future water treatment demands. The full wording of the scope of services as they relate to this report is given in Appendix B.

The draft of this report dated 30 September 1998, recommended a series of bench scale tests be conducted to better define possible alternatives that arose during the period preparatory to writing the draft report. This Final Report includes the results from these tests, and identified the best coagulant chemical, disinfectant, and most appropriate chemical for inactivating nematodes in the raw water traversing the conveyance system from the intake to the Zar WTP. The results of tests for trihalomethane formation, using chlorine at the plant and at the Intake Pump Station, and the test comparing the proposed alternative application point for powdered activated carbon (PAC) compared to the existing application point, are also included in this final report. The report incorporates all applicable comments on the draft report received from USAID, Water Authority of Jordan (WAJ), Dr. Murad Jabiy Bino, Consultant to WAJ, and the German funding agency, Kreditanstalt für Wiederaufbau, and the Japanese funding agency, Japan International Cooperation Agency (JICA).

This report was prepared by Robert D. G. Monk, a CDM Consultant, under the general direction of the Project Manager, David A. Ogden, of CDM Amman, Jordan. CDM acknowledges the ready assistance given by the Minister of Water and Irrigation, His Excellency Dr. Hanan Mulki, and other MWI/WAJ personnel, in furnishing information and for their helpful review comments of previous drafts. CDM would also like to thank the acting Zar WTP Manager, Mr. Saleh Malkawi, and his staff for their cooperation during the course of gathering data and for participating in the bench-scale tests. CDM also acknowledges the help and direction given by Mr. Alex Sundermann of USAID.

CDM trusts this combined assistance will contribute to a permanent solution to the problems experienced and to the continued wellbeing of the citizens of Amman.

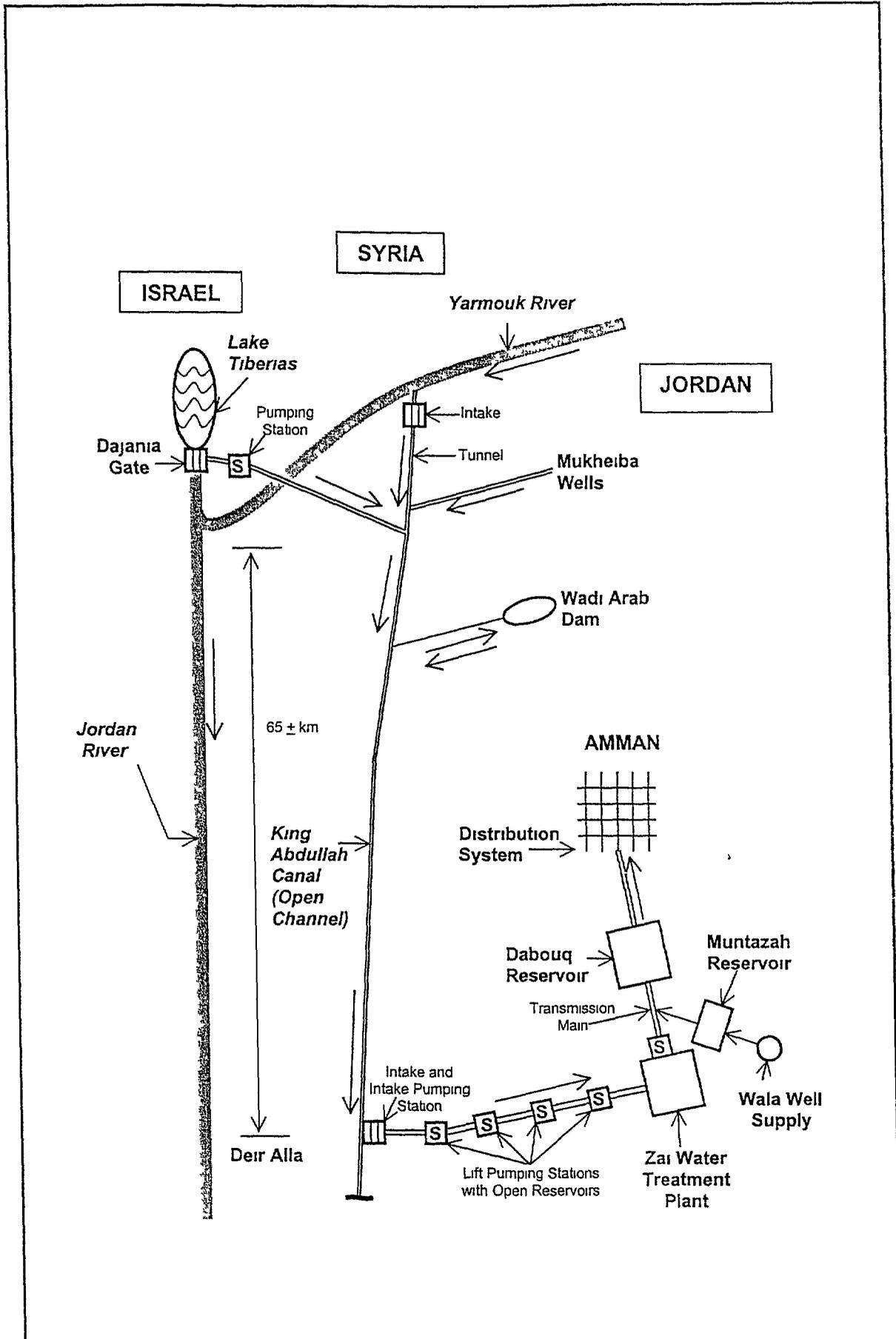
2.0 Background

The Zaī WTP was designed to treat 123,000 cubic meters per day (m^3/d) and to provide potable water to the western part of the city of Amman. The water source for the plant is the King Abdullah Canal (KAC) which transports mixed surface waters from Lake Tiberias at the Dajūnī Gate, the Yarmouk River, and occasionally the Wādī Al Arīb Dam. Ground water from the Mukheibī Wells is also piped to the KAC. The KAC is used primarily to convey water for irrigation purposes down the eastern side of the Jordan River Valley.

The water to be used for the city of Amman is diverted from the KAC at Deir Alla, where it is screened, and then conveyed through a series of 5 pump stations, balancing tanks, and pipelines to the Zaī WTP. The treated water is then pumped to the Dabouq Reservoir and from there conveyed by gravity into the city. This overall conveyance and treatment system is shown on the Schematic Diagram of the Deir Alla-Zaī Conveyance System of Figure 2-1.

In early July, 1998, there was an incidence of bad taste and odor in the treated water delivered from the Zaī WTP to the city. This taste and odor persisted through July and well into August. A number of Jordan Government agencies and international consultants investigated the problem and concluded that the taste and odor originated from algae in the water and that the treatment plant processes and operations were insufficient to deal with the magnitude of the problem. Investigations initiated to determine the source and reasons for the outbreak also identified dead and live nematodes in the raw waters and dead ones in the treated waters. While the exact sources are not known for sure as yet, nematodes are likely to be coming from the Yarmouk River and could also be developing in any silt and organic deposits in the bottom of the KAC (between dredgings). In wet weather, they could originate in soils and be washed into the canal with surface stormwater run off. There are also indications that they could have been breeding in the plant's filters.

Currently, the Deir Alla Zaī WTP-Dabouq Water Conveyance System is at an advanced design phase for doubling systems capacity by Tokyo Engineering Consultants for JICA. CDM reviewed these proposals as part of the preparation for this report and comments on them are included herein.

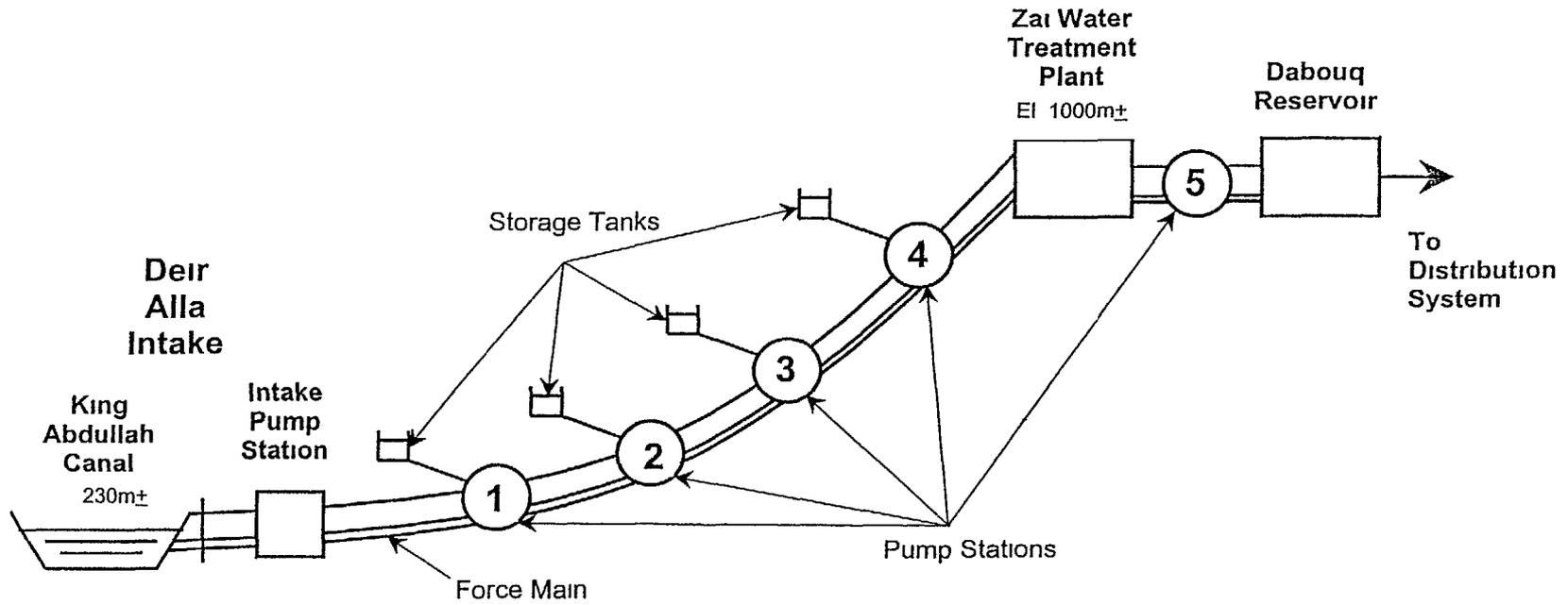


3.0 System Description

The system reviewed under the terms of the scope of work of this contract was the Deir Alla Zai WTP System. This system includes the raw water intake off the KAC at Deir Alla, screens, the Intake Pump Station and 1,200 mm diameter force main to Pump Station 1, Pump Stations 2, 3, and 4, with storage (balancing) tanks and connecting 1,200 mm diameter force mains, the Zai WTP, including the raw water regulating (balancing) reservoir, and a two compartment clearwell. From the Zai WTP, the treated water proceeds through Pump Station 5 and 1,200 mm diameter force main and on to the Dabouq (Terminal) Reservoir. Water is transmitted from the Dabouq Reservoir via a 900 mm diameter pipeline to the city's distribution system. The Wala Well supply connects into the 900 mm force main between the Zai WTP and Dabouq Reservoir. This well supply is pumped into the Muntazah Reservoir and from there flows by gravity. The KAC is an open canal used primarily for irrigation and is approximately 65 kilometers in length from its start to the point of the Deir Alla intake. The water in this canal is slow moving and, therefore, the canal will tend to accumulate silts, muds, and organic matter on its floor. This accumulation, combined with the long detention time and exposure to sunlight, promotes algae growths. In order to reduce these algae growths, the addition of ferric chloride to the raw water at the head of the open canal has been recently initiated to precipitate out phosphorous in the water, at the recommendation of the German water specialist Dr. Christoph Czekalla of CONSULAQUA, Hamburg. Phosphorous is one of the chemicals that enhances algae growth. The conveyance and treatment system is shown graphically in Figure 3-1.

The balancing tanks at Pump Stations 1, 2, 3, and 4 are open to the atmosphere and float on the system, that is, the water is not routed through them. The water level simply rises and falls within them, depending on the imbalance between water delivered and water pumped. Consequently, the water in these tanks can stagnate and grow algae. This can result in slugs of water, loaded with algae and potential algae secreted taste and odor compounds, entering the conveyance system and the Zai WTP. To minimize this highly algae laden water entering the conveyance system and the Zai WTP, the operators occasionally flush this water out via the reservoir overflows.

The Zai WTP was constructed in the mid 1980s. The treatment processes are conventional and consist of flow balancing and control, mechanical rapid mixers and flocculators for chemical coagulation and flocculation, rectangular, horizontal flow type, sedimentation basins, dual-media, rapid gravity filters, and a two compartment treated water clearwell. Chemicals used include potassium permanganate for pre oxidation and is an aid in taste and odor control, powdered activated carbon (PAC) as the primary chemical for taste and odor control, aluminum sulfate (alum) is the primary coagulant, cationic polyelectrolyte (polymer) as a coagulant aid, anionic polymer as a flocculation aid, and chlorine to control aquatic growth, to contribute to the control of taste and odor, and to function as the primary disinfectant. Provision was also included in the original design to add sodium hydroxide (caustic soda), but this chemical is not needed and was never used. Provision was made in the design for a spare chemical which has never been used either. The pH of the raw water is normally greater than 8.0. This is well above the optimum pH for alum coagulant. The pH of the water leaving the plant is 7 plus. This indicates that excess alum is being used to depress the pH closer to the optimum value. The anionic polymer has been relocated from the settled water application point to the last stage of flocculation to aid in floc formation.



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SCHMATIC PROFILE
OF DEIR ALLA-ZAI-DABOUQ SYSTEM

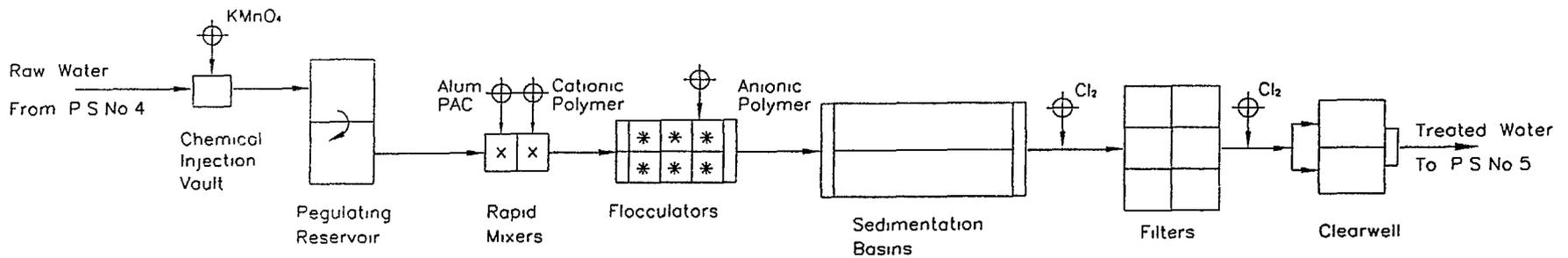
Figure 3-1

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Figure 3-2 shows the Process Flow Schematic of the Zai WTP's treatment train and the chemical application points currently used. Figure 3-3 is a general layout drawing showing all the treatment components at the site. Table 3-1 lists the treatment process components and their respective design criteria.

At a meeting with Eng. Koussu Quteishit, Secretary General of the Ministry of Water and Irrigation, and other Ministry personnel, the question was raised about the Israelis' approach to water treatment. It was suggested that Jordan should take the same approach, including the pretreatment method the Israelis use. Israel's main water source is Lake Tiberias. They pump the water into a canal which discharges into a large open reservoir. As the water enters the reservoir, a coagulant and an acid are added, and hydraulic flocculation follows. The water then traverses the reservoir, which is in fact a large sedimentation basin. At this time, other than the addition of chlorine, the water receives no further treatment. The Israelis have conducted pilot plant studies and now plan to add ozonation and filters after the settling basin reservoir at the same site. In effect, then, apart from the addition of ozone, the treatment process will be the same as that used at the Zai WTP. In fact, the pretreatment at the Zai WTP is a more controlled and effective system than the Israeli pretreatment system. CDM does not recommend other forms of pretreatment than those included in this report. The more concentrated treatment processes are, the more manageable, effective, and efficient they will be. To diversify treatment processes complicates management, communication, and the control of the overall treatment process.



LEGEND

- x Mechanical Mixer
- * Flocculator
- ⊕ Chemical Application Point
- KMnO Potassium Permanganate
- Cl₂ Chlorine
- P S Pump Station

NOT TO SCALE

PROCESS FLOW SCHEMATIC

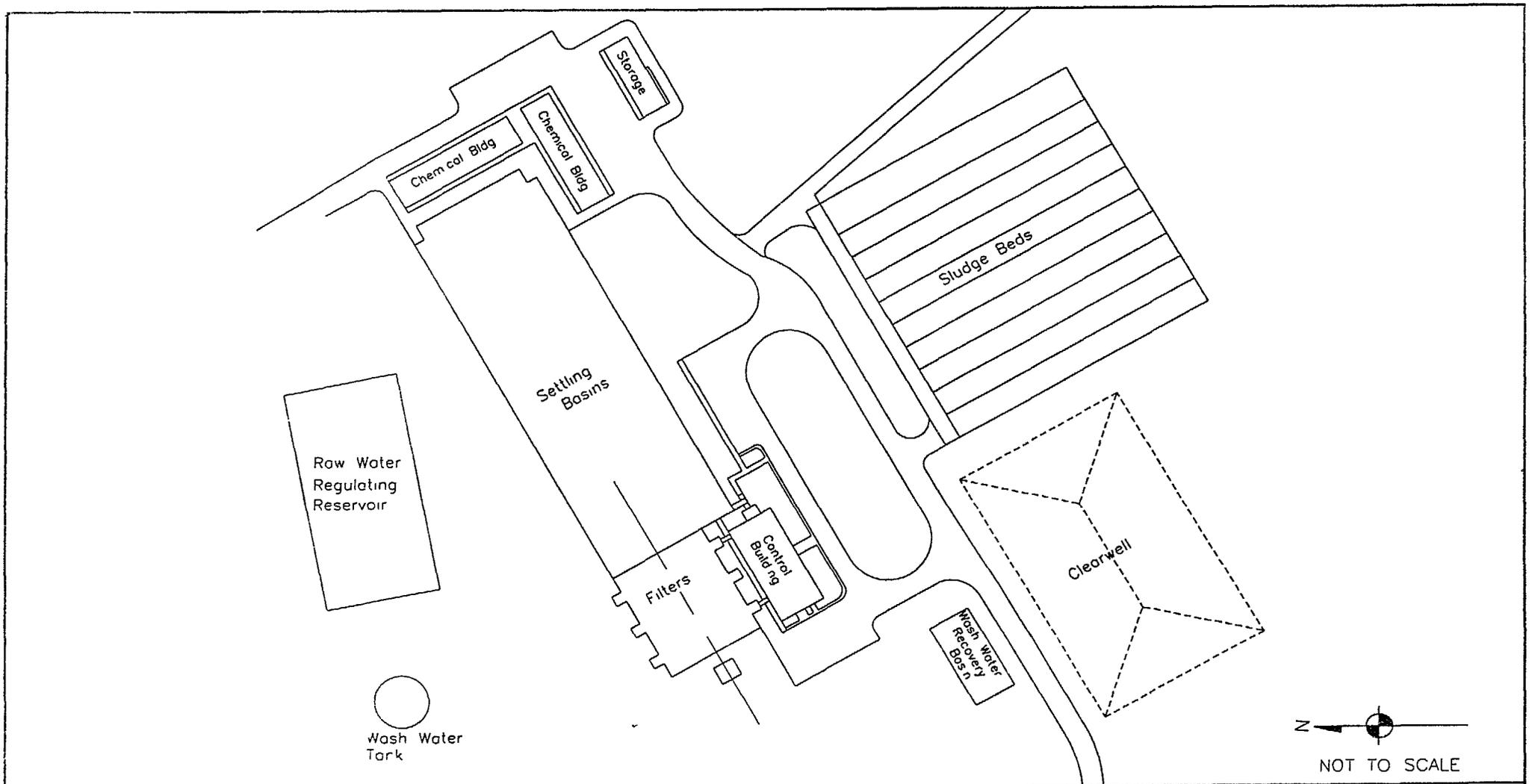
Figure 3-2

ZAI WTP

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NOT TO SCALE

ZAI WATER TREATMENT PLANT
LAYOUT PLAN

Figure 3-3

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ZAI WTP

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Plant Capacity			Settling Basins		
Nominal Design	Mm ³ /a m ³ /d	45 123 000	Basins	trains	2
Raw Water Regulating Reservoir			Inside Dimensions Each	m	18x95
Reservoir	compartments	2	Water Depth	m	4.5
Inside Dimensions (each)	m	32x65	Volume Each	m ³	7 695
Water Depth	m	5.25	Volume Total	m ³	15 390
Volume	m ³	10 350	Detention Time	minutes	180
Max Detention Time	hours	2	Basin Loading	m ³ /d/m ²	36
Rapid Mixing			Average Velocity	m/min	0.53
Volume of Chamber	m ³	25	Weir Overflow Rate	m ³ /d/m	150
Mixer No 1	number	1	Weir Length Each	m	408
Velocity Gradient	sec ⁻¹	1 000	Weir Length Total	m	816
Mixer No 2	number	1	Sludge Removal		
Velocity Gradient	sec ⁻¹	700	Travelling Bridge	number	2
Flocculation Basins			Bridge Speed Maximum	m/min	3
Basins	trains	2	Bridge Speed Minimum	m/min	0.3
Compartments	number	6	Pumps Each Bridge	number	5
Inside Dimensions Each	m	5.8x18	Nominal Pumping Rate (1 Pump)	L/min	340
Water Depth	m	4.5	Nominal Pumping Rate Each Bridge	L/min	1 700
Volume Each	m ³	470	Volume of Liquid Assuming One Pass	m ³	160
Volume Total	m ³	2 820	Per Day Each Basin at 1 m/min		
Detention Time	minutes	33	Sludge Drying Beds	number	10
Velocity	m/min	0.55	Maximum Liquid Surface Area One Bed	m ²	605
Flocculators (Two Speed)			Maximum Liquid Surface Area Total	m ²	6 050
First Row	number	6	Maximum Volume of Liquid - One Bed	m ³	472
Velocity Gradient	sec ⁻¹	100	Maximum Volume of Liquid Total	m ³	4
Second Row	number	6	Dual Media Filters		
Velocity Gradient	sec ⁻¹	80	Filters	number	6
Third Row	number	6	Area of One Filter	m ²	88.32
Velocity Gradient	sec ⁻¹	60	Filtration Rate Per Filter	L/min/m ²	160
			Filter Profile		
			Anthracite	mm	600
			Sand	mm	300
			Gravel	mm	300
			Filter Underdrain System	perforated	

Table 3-1: Zai Water Treatment Plant -- Design Criteria

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Backwash System

Maximum Backwash Rate	L/min/m ²	1 000
Maximum Backwash Rate	m ³ /min	88 32
Filter Agitators	rotary	
Agitators Per Filter	number	4
Operating Pressure	kg/cm ²	7
Wash Rate	L/min/m ²	23
Wash Rate Per Filter	m ³ /min	2
Filter Agitator Pump	number	2
Capacity – Each Pump	m ³ /min	2 0

Wash Water Tank

Tank	number	1
Tank Diameter	m	16
Water Depth	m	8 5
Depth of Usable Water	m	7 0
Volume of Usable Water	m ³	1 420
Capacity/Volume for 10 Minute		
Normal Backwash Rate	ratio	2 1
Wash Water Pumps		
(Including One Standby)	number	2
Average Pumping Rate Per Pump		
(Includes Water for Plant Operation)	m ³ /min	8 4

Wash Water Recovery Basin

Basin	number	1
Volume of 10 Minute Filter Backwash		
Per Filter	m ³	710
Volume of Filter Agitator Wash	m ³	10
Volume of Wash Water Per Wash	m ³	720
Basin Interior Dimensions	m	12x26
Average Water Depth	m	4 6
Freeboard to Overflow	m	0 20
Volume of Storage	m ³	1 440
Capacity/Volume for 10 Minute		
Normal Backwash Rate	ratio	2 1
Wash Water Recovery Pumps	number	2
Capacity Per Return Pump	m ³ /min	7 2

Clearwell Storage

Reservoir	number	1
Interior Dimensions	m	50x81
Water Depth Maximum	m	5 75
Volume	m ³	21 400

Chemicals

	Dosage	Average	Maximum
Chlorine Pre Treatment	mg/L	3 00	6 00
Chlorine Intermediate	mg/L	1 00	3 00
Chlorine Post Treatment	mg/L	0 50	1 00
Aluminum Sulfate	mg/L	10 00	40 00
Caustic Soda (25%) (Sodium Hydroxide)	mg/L	5 00	10 00
Activated Carbon	mg/L	2 00	10 00
Potassium Permanganate	mg/L	2 00	5 00
Polyelectrolyte Cationic	mg/L	1 00	2 00
Polyelectrolyte Anionic or Nonionic	mg/L	0 02	0 04

Table 3-1: Zai Water Treatment Plant – Design Criteria – Cont'd

4.0 Water Quality

The raw water quality in the KAC at the Deir Alla offtake fluctuates due to the multitude of water sources, the long travel and detention time in the KAC, possible releases from the Wadi Al-Arab Dam, the nutrient proportions in the water, and seasonal weather conditions. The reported range of the normal raw water quality parameters for a surface water source for treated potable water, such as turbidity, color, fecal coliform, algae, pH, hardness, alkalinity, and total organic carbon (TOC), are generally not extreme, considering the source water and conveyance systems. Stanley Consultants Inc. has reported some occasionally very high levels of TOC, which could result in a high incidence of trihalomethane (THM) formation following chlorine addition to the water at the Zar WTP. Dr. Czekilla reported that the algae density in the raw water during July and August was considered low to moderate. He also stated that the levels of algae favoring nutrients, phosphate and nitrate, in water from Lake Tiberias were low, whereas the nutrients in the Yarmouk River water were ten fold more. The algae identified by the Government and the Royal Scientific Society Laboratories did include a variety of taste and odor producers. Additionally, the raw water was found to contain nematodes. These have been identified as the free living (non parasitic) type, and of themselves are not a threat to public health. However, they do feed on microorganisms, and can harbor pathogens and viruses in their digestive systems. Therefore, a public health concern should arise whenever nematodes are present in the finished water.

Although only dead nematodes have ever been detected in the finished water, CDM believes it is prudent from both health and aesthetic standpoints to control nematodes through the optimization of plant processes for both disinfection and particle removal (sedimentation and filtration). CDM's recommendations, discussed later in this report, provide the means to accomplish this, in combination with the proper operation of the plant's treatment processes.

The water produced by the Zar WTP, until the start of the taste and odor incidents in July and August of 1998, had met the drinking water quality standards of the Jordan Standard Specification 286/1997. The referenced taste and odor events were a surprise to all concerned. Nothing like this had happened before. Often at plants in the United States, and other countries that irregularly experience taste and odor problems, the operators do not coincidentally identify the problem in the plant until they receive consumer complaints. It is difficult for managers and operators who run a plant continually to identify taste and odor themselves. Even if they are anticipating a regular seasonal taste and odor event, and perform threshold odor number (TON) tests on the water, tastes and odors can still pass through into the distribution system undetected. A more sophisticated testing system is often used, consisting of a panel of personnel from people not associated with the operation of the plant, and who have nose sensors that are not influenced by extraneous things like smoking, perfume use, etc., to conduct regular Flavor Profile Analyses (FPA). This panel must consist of people that fit a vigorous specification, are available regularly, and conduct their analyses in rooms specially insulated from outside odors that could impact upon the results. Even where this method is used, taste and odor can and do still get through the plants.

In the future, it can be expected that the raw water quality will deteriorate somewhat. This is an inevitable result of residential, industrial, and agricultural development increasing in the water source catchment areas. With the planned plant expansion, an additional 45 million m³/year (123,000 m³/d) of raw water will be used. Where this water comes from will cause a

minor change in the water quality. However, it is not anticipated that a decrease in water quality will be sufficient to warrant any major changes to the existing treatment processes or additional processes outside the recommendations of this report. It would be prudent for all the responsible Government regulating agencies to be mindful of the implications of not strictly enforcing existing control regulations, the failure of which could impact water quality. However, the control and management of large parts of the watershed areas are outside the direct control of Jordan and its regulatory agencies. Future, more stringent treated water quality requirements may be more of a driving force for process changes, but even this is unlikely except for the possibility of the addition of ozone or another primary disinfectant to meet lower future disinfectant by-products (DBP) regulations. Even then, Jordan should not necessarily follow the United States' criteria. The potential dangers of DBPs arise from drinking large amounts of water containing high levels of DBPs over a long period. The question is, do the people of Jordan drink as much tap water as in the US? If not, then any DBP regulation set by Jordan should reflect this difference. Worldwide, there is still a wide divergence of opinion over THM and other DBP levels within the regulating countries.

The quality of the water leaving a water treatment plant is not necessarily the quality coming out of the consumer's tap. It is very important to maintain a tight transmission and distribution system to protect this water from contamination. A disinfectant residual still in the water at the farthest location in the system will help to ensure bacteria free water. The lack of a chlorine residual is an indicator of possible contamination through a cross connection or by some other means. However, since the amount of residual disinfectant in the treated water is insufficient to disinfect contaminated water entering the system, vigilance is necessary to check for signs of trouble by regularly testing to ensure that a residual is being maintained everywhere throughout the system. Lack of a residual is an indicator of trouble. To spend a lot of time and money to produce the high quality of water the Zu WTP is capable of producing only to have it degraded in the distribution system would be unfortunate and dangerous.

5.0 Potential Causes of the Taste and Odor and Nematode Problems

The quality of the raw water sources and the warmer summer temperatures in early July, 1998, initiated the taste and odor producing algae in the raw water sources, the long conveyance systems promoted their further development, and the Zai WTP management and operators were unable to treat the water at full plant capacity effectively and responsively. This was in part due to inexperience, but primarily due to insufficient powdered activated carbon (PAC) metering capacity. The taste and odor events were far and away greater than any experienced before and of such a magnitude that the plant staff was unable to respond quickly enough to avoid the catastrophe that resulted. The plant had run successfully for 10 years without an incident like this. At no time was more than 10 milligrams per liter (mg/L) of PAC needed. However, in this incident water production had to be cut back to allow the existing feeders to add 60 mg/L of PAC to the water. Although the operations manual indicated there may come a time when 100 mg/L of PAC may be needed, it did not go into any detail as to how this could be implemented. However, each of the two PAC volumetric feeders are rated at 2.7 m³/d—about 10 mg/L at the design flow of 123,000 m³/d. From the data CDM has collected, the PAC feeders cannot feed PAC in excess of about 10 mg/L at the design flow. PAC is the primary chemical provided by the designers to control taste and odor. The plant had successfully controlled taste and odor in the raw water (in 1997, for example) by using an average of only 1.2 mg/L of PAC, plus 1.3 mg/L of potassium permanganate and 2.8 mg/L of chlorine. CDM recommends the PAC feeders and slurry diaphragm pumps be replaced with units capable of dosing PAC at up to a total of 70 mg/L based upon Dr. Czekalla's test results at the time of the taste and odor event. The capacity of each unit should be 35 mg/L as discussed in more detail in Section 6.10.

The multiple water sources supplying raw water to the Zai WTP contain algae and nematodes. This is something that cannot be easily controlled or economically addressed. The scope of work related to this report is limited to the Deir Alla Zai WTP-Water Conveyance System, however, the fact that the raw water sources do contain algae and nematodes must be assumed as a given, and their impact on the treatment plant minimized by limiting their growth in the conveyance systems. Because the water in the KAC is primarily for irrigation purposes, the canal is used to store water. Thus, the water velocity in the canal is often slow, causing silt, mud, and organic matter to settle out and accumulate on the canal floor. This then becomes a potential breeding ground for nematodes and a further source of taste and odor. Adding ferric chloride to precipitate out phosphorous, as is currently practiced, can actually exacerbate the situation. When these bottom deposits are resuspended, severe algae blooms can result due to the resuspended phosphorous. These blooms could have the potential to cause severe taste and odor problems. Similarly, the resuspension of decaying organic deposits due to increased water velocities, or other reasons, will further add to the taste and odor. The resuspended nutrients will encourage algae blooms.

The contributing factors for an algae bloom are complex. These include the correct combination of elements that go to contribute to an algal bloom, nutrients and their respective combination, water temperature, sunlight, and runoff. These are difficult to predict with any degree of accuracy. Storm runoff from the areas traversed by the canal can also contribute waters that increase the nutrients in the water and therefore the potential for algae proliferation. These run-offs may also add to the nematode population in the canal water, as well.

The often stagnant water in the pump station balancing tanks of the Deir Alla Zu WTP Conveyance System is a further potential breeding ground for taste and odor producing algae. The raw water force mains up to the Zu WTP can also have aquatic growths that develop on walls of the pipes and that can further produce taste and odor.

The CDM report of 13 August 1998 and a press reports of 21 September 1998 and subsequently, all state that, coincidental with the taste and odor event, the water was "turbid" and "murky". Water quality reports for the treated water leaving the Zu WTP at the same time indicate that the turbidity of the water was low. The question then is how did the water become turbid or murky? While it was not in CDM's scope of work to assess the distribution system, one scenario could be that the water was contaminated by discharges from the Wala Well Supply that sends well water into the 900 mm diameter pipeline before the Dabouq Reservoir.

6.0 Possible System Modifications

There are a number of modifications that can be made to the conveyance systems and to the treatment process units that will, first, reduce the potential taste and odor events and/or their magnitude, and, second, be able to successfully treat for such events when they occur in the future. There are other modifications that will increase the particulate removal efficiency of the Zai WTP and these are discussed in the following sections.

6.1 King Abdullah Canal (KAC)

Although the KAC conveyance system is outside the scope of this report, it must be recognized as a major potential contributor to the taste and odor and nematode problems experienced in 1998. It would not be prudent for CDM to make recommended modifications to the Zai WTP without taking into account the water source and quality.

In order to limit the deterioration of the quality of the raw water sources, control should be exercised over the surface water discharges into Lake Tiberias, the Yarmouk River, and the KAC itself. This may mean that international treaties must be agreed to. Care should also be exercised as to when and how much water is discharged from the Wadi Al Arab Dam.

CDM does not believe the use of ferric chloride to precipitate phosphorous in the canal is advisable if the current operational practices of the KAC are continued. While some short-term benefits in controlling algae could result from this practice, it is CDM's opinion that adding ferric chloride ultimately increases the risk of developing a large scale algae bloom in the canal by causing phosphorous and organic matter to settle out. These deposits, if allowed to collect and then be resuspended, could provide nutrients for such an algae bloom and result in an extremely high taste and odor event. If bottom deposits cannot be avoided altogether, then a way to resuspend this material on a regular basis, before decomposition starts and the phosphorous deposits get too large, should be investigated and implemented.

Prechlorination of the water in the KAC is also not advisable. A high amount of chlorine would be necessary to achieve a residual over the canal's 65 km length, and this would result in high levels of disinfectant by-products, such as trihalomethanes (THMs). Consideration must also be given to the effects of adding chlorine and ferric chloride to water used primarily for irrigation of crops.

Any pretreatment should consist of silt separation only, as proposed at Pump Station No. 1. To build larger pretreatment facilities will add costs, complicate operations, and make parts of the existing Zai WTP redundant. By implementing the recommendations of this report, the plant will be able to treat water currently and in the foreseeable future. The addition of copper sulfite or some other algicide into the top of the canal would, in our professional opinion, be better than using ferric chloride. However, the use of copper sulfate or any other algicide should be investigated as to the impact these toxins would have on soils subject to irrigation. It may be that copper sulfite need only be used on an intermittent basis, not continuously. This will minimize the effect on agricultural soils.

6.2 Dead Algal Water Conveyance System

Copper sulfate is now being added to the raw water at the intake. This should effectively inactivate the algae but not necessarily eliminate taste and odor from this source. Dead algae can still result in taste and odor and algae-secreted taste and odor compounds will likely be in the water already. Copper sulfate will not remove these. However, dead algae are easier to remove by coagulation, flocculation, and settling at the Zai WTP than live algae. The removal of dead algae would reduce potential algae clogging of the plant's filters. However, because the balancing tanks at the pump stations along the raw water conveyance system stagnate, algae blooms will still occur in these balancing tanks, which could result in slugs of algae and/or tastes and odors reaching the Zai WTP. The best solution to this particular problem is to modify the piping at each tank, so as to route the water through the reservoirs, and to add baffling to each tank to eliminate dead areas where algae could flourish. Figures 6.2-1, 6.2-2, 6.2-3, and 6.2-4 show the re-piping necessary to eliminate the stagnation, Figure 6.2-5 shows details of the type and configuration of baffles recommended to avoid short circuiting through the tanks.

Stanley Consultants Inc. has designed settling basins at the Pump Station No. 1 site. CDM has reviewed the final design drawings for the basins. These basins are intended to promote the deposition of abrasive silts in the raw water to minimize wear on the pump impellers. The basins are designed to accumulate this silt and to facilitate its removal by front-end loaders, loaded on to trucks, and hauled off site to a disposal area on an intermittent basis.

Since the taste and odor event, Stanley has further recommended that consideration be given to adding ferric chloride to the water entering these basins. CDM does not recommend this practice. Between the intermittent cleanings organic matter will accumulate along with the silt and be the cause of tastes and odors. Also, on the recommendation of Stanley Consultants, copper sulfate is now being added at the Intake Pump Station to inactivate algae and help control taste and odor. CDM recommends that potassium permanganate be added here instead of the copper sulfate. Potassium permanganate is already being used in the Zai WTP. It should work as effectively as copper sulfate in inactivating algae. In addition, as an oxidant, it will better aid in the control of taste and odor. By adding it here instead of at the inlet to the Zai WTP as currently practiced, the contact time will be extended and, therefore, its effectiveness enhanced. Further, potassium permanganate will keep the pipelines clean of aquatic growths and eliminate potential taste and odor from this likely source. Confirmation testing of potassium permanganate and other potential chemicals is further discussed in the next section of this report.

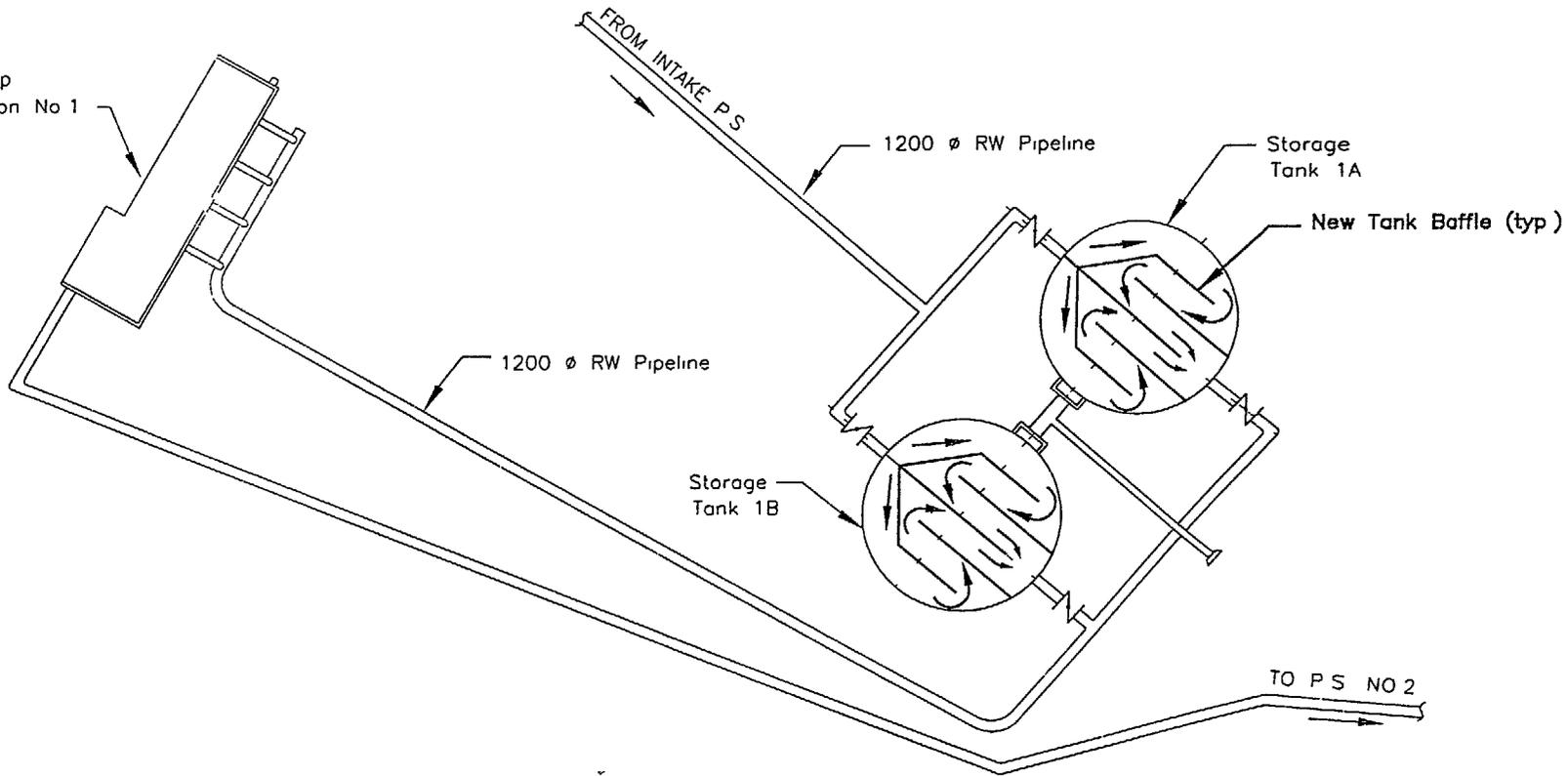
CDM recommends that the settling basins at Pump Station No. 1 be operational before the baffling and piping modifications suggested above are implemented. This will avoid the deposition of abrasive silts in the balancing tanks.

6.3 Nematode Inactivation and Disinfection

The life cycle of free living nematodes consists of the egg, four larval stages, and one adult stage. These are generally microscopic in size but can be removed from raw water through well operated, conventional water treatment plants such as the Zai WTP. Thus far, only dead nematodes have ever been detected in the plant's treated water. However, it is more



Pump Station No 1



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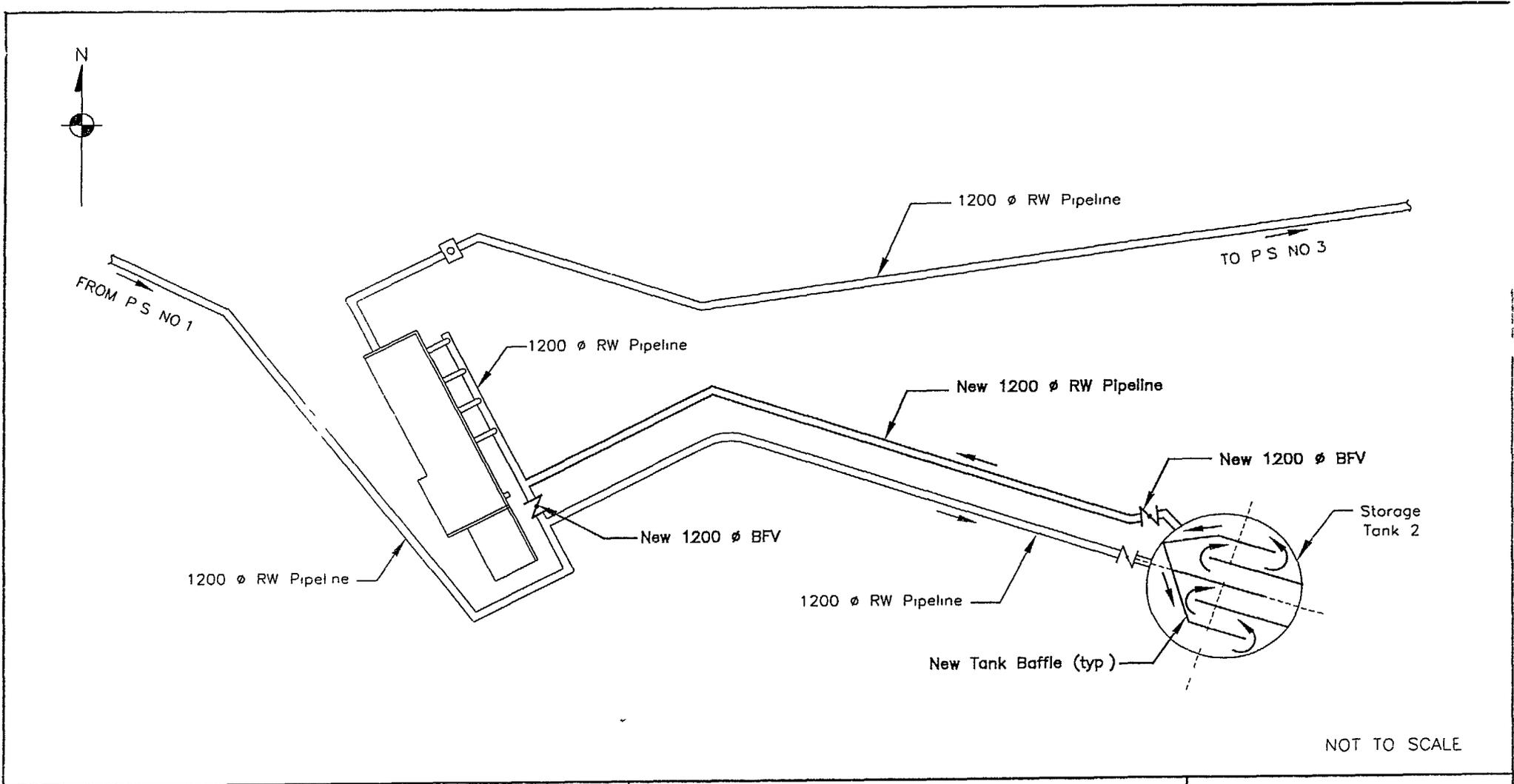
PUMP STATION NO 1

Figure 6 2-1

STORAGE TANK MODIFICATIONS

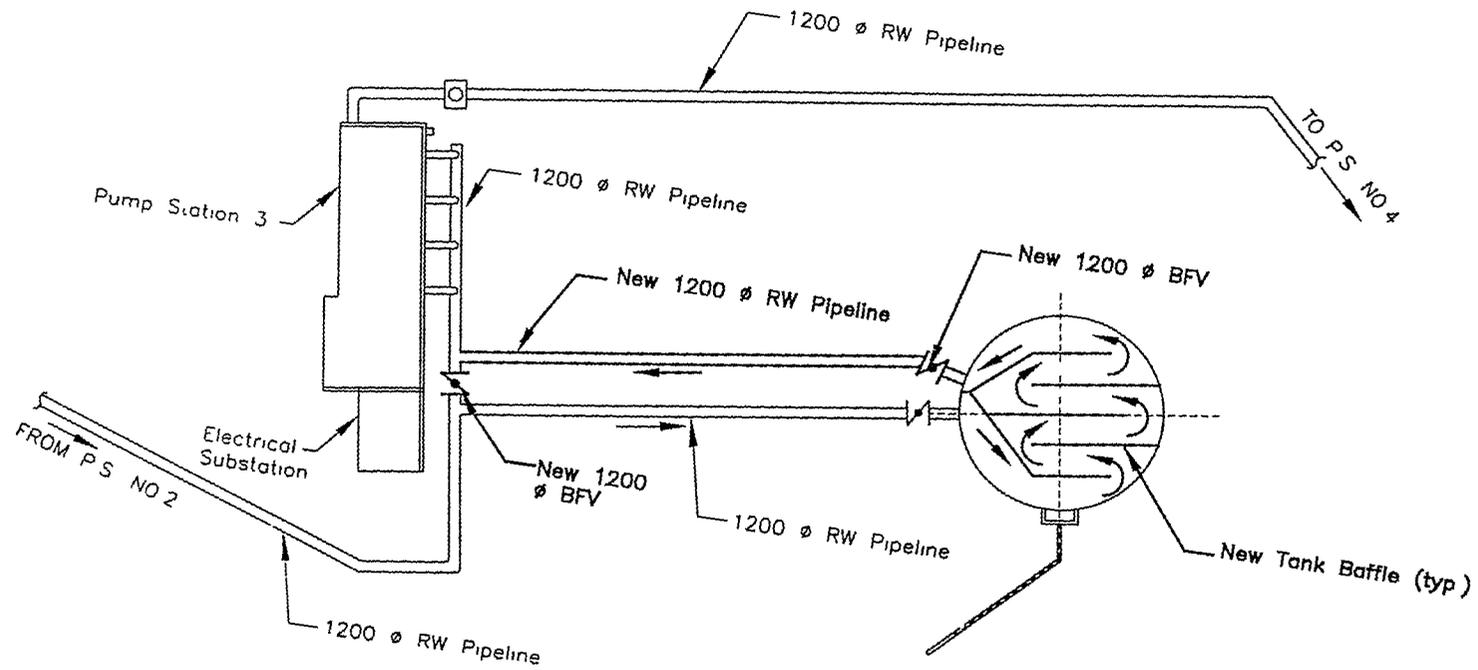
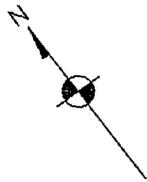
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CDM Camp Dresser & McKee International Inc	PUMP STATION NO 2	Figure 6 2-2
	STORAGE TANK MODIFICATIONS	NOV 98

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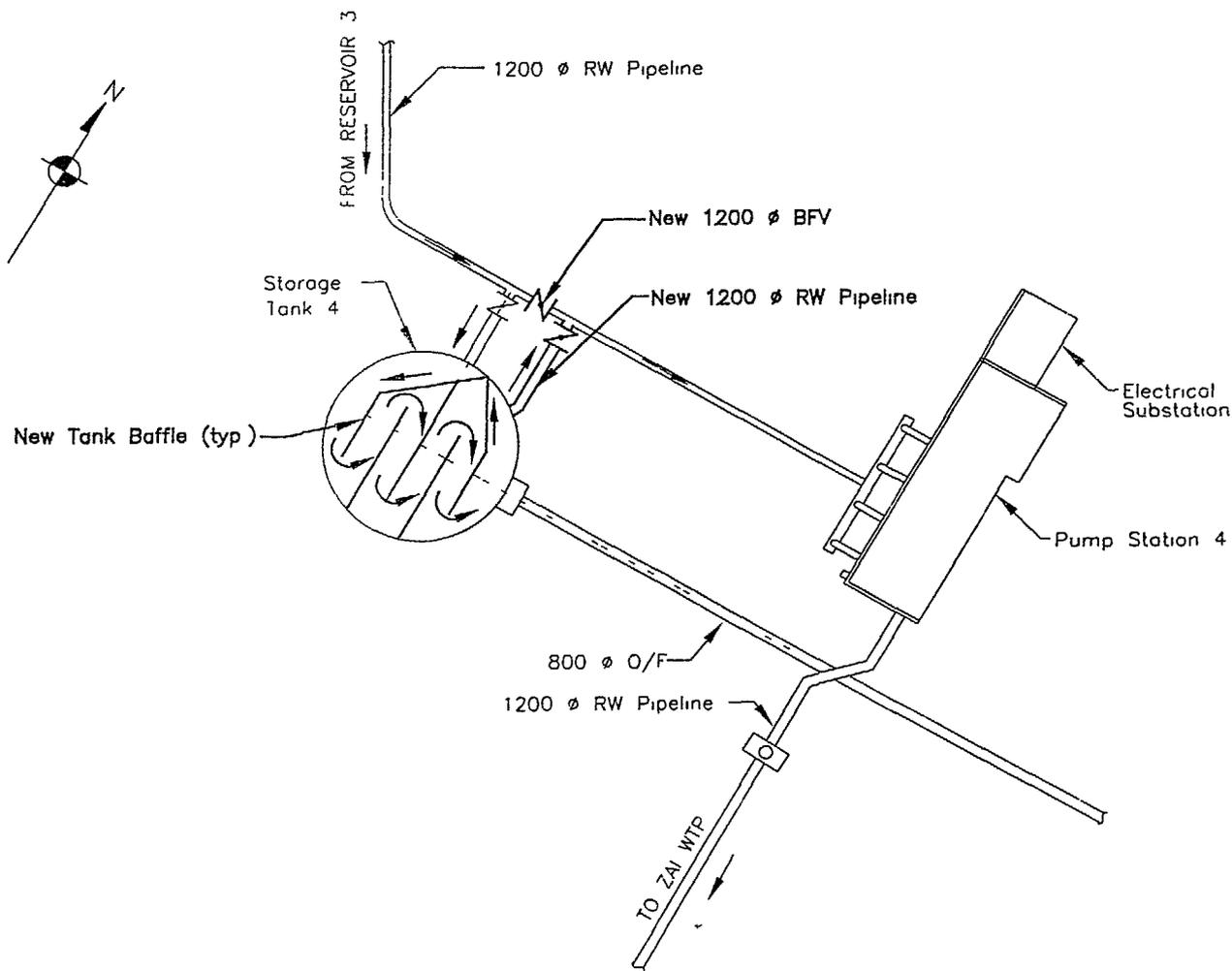
PUMP STATION NO 3
STORAGE TANK MODIFICATIONS

NOT TO SCALE

Figure 6 2-3

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24C



NOT TO SCALE

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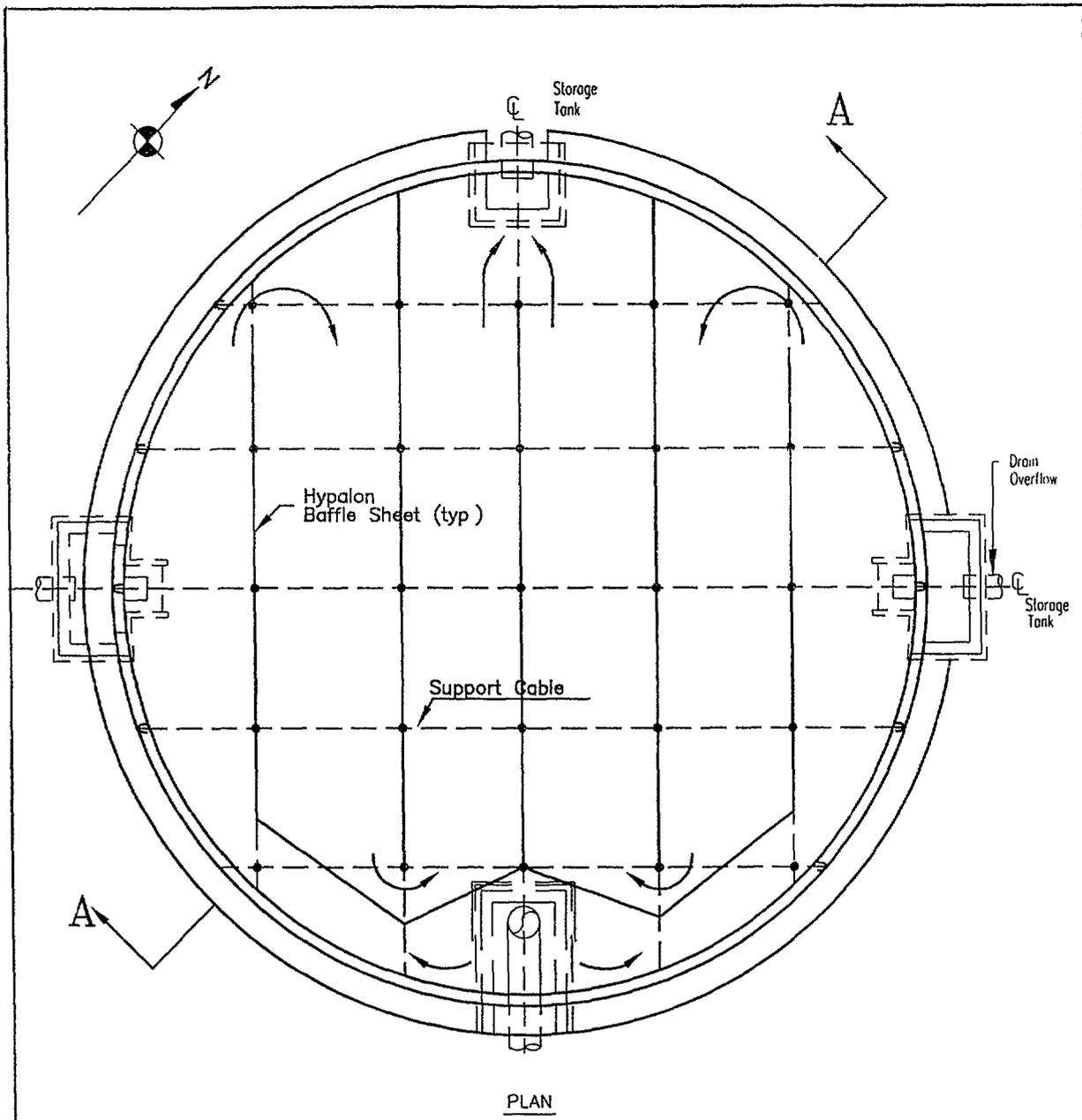
PUMP STATION NO 4

Figure 6 2-4

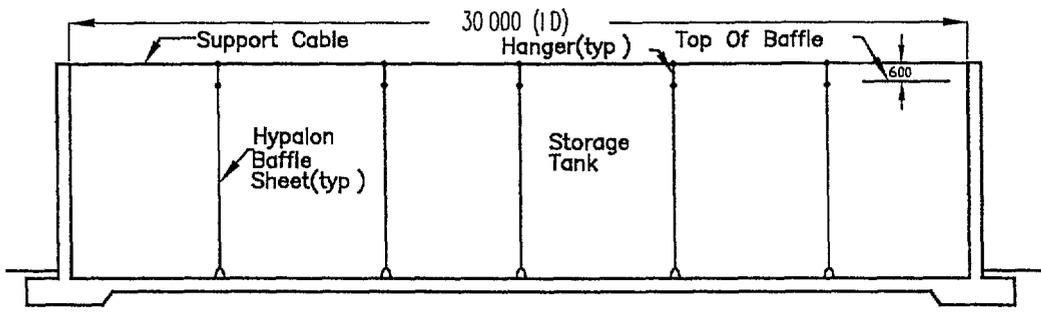
STORAGE TANK MODIFICATIONS

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24d



PLAN



SECTION A-A

NOTE THIS DETAIL IS FOR
TANK AT P S NO 1
OTHER TANKS SIMILAR

NOT TO SCALE

CDM Camp Dresser & McKee International Inc

STORAGE TANK BAFFLING
(TYPICAL OF ALL TANKS)

Figure 6 2-5

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likely these nematodes will be removed if they are inactivated before reaching the coagulation stage of the plant. By doing this, it also eliminates the chance of nematodes breeding in the filters of the plant. To do this, a disinfectant could be added to the water at some stage within the raw water conveyance system such that the product of the disinfection concentration (C, in mg/L) and contact time (T, in minutes) is adequate to inactivate the nematodes.

Nematodes are not easily inactivated by chlorine. These require a relatively high dose and/or contact time for effective inactivation. Alternatively, a nematicide chemical could be used. However, CDM has not identified one that is safe for use in potable water. Potassium permanganate may also be effective in inactivating nematodes if the dose and/or contact time is adequate. As it is already recommended to inactivate algae, it is the most cost-effective alternative.

There is not a lot of information available on the inactivation of nematodes. Therefore, based upon the recommendations of the Draft Report of 30 September 1998, a series of tests were performed to help identify a disinfectant, or determine the effectiveness of potassium permanganate for nematode inactivation, and the respective effective doses. It was assumed the chemicals will be applied at the Intake Pump Station. Minimum travel times of the water in the conveyance system to the plant at half plant capacity of 61,500 m³/d and the future full expanded plant capacity of 246,000 m³/d were used. Various disinfectants and potassium permanganate were used at different doses (C), and contact times (T) for each. From these tests it was possible to identify the effect the various disinfectants and potassium permanganate had on nematodes. The disinfectants tested were chlorine, chloramine, and chlorine dioxide. Potassium permanganate and chlorine were also tested together. The test results summary is provided in Appendix C.

Based upon bench-scale Test No. 1 results, the use of chlorine to aid in nematode inactivation is not possible because of the high levels of trihalomethane (THM) by-products produced. Of the four oxidants used in the test (chlorine dioxide, chlorine, chloramine, and potassium permanganate), chlorine dioxide was the most effective in inactivating the test nematode *Cephalobus*. Test No. 2 showed the synergistic benefit of using chlorine and potassium permanganate together. It is expected that using chlorine dioxide and potassium permanganate together will have a similar, or better, nematode inactivation result than if these chemicals are used separately.

The advantages of using chlorine dioxide are that it will result in minimum THM formation, will aid in nematode inactivation, will disinfect the water, and will contribute to taste and odor control, thereby reducing the PAC dose necessary at the Zai WTP. This is discussed further in Section 6-10, "Taste and Odor Control."

Considering, then, the use of chlorine dioxide as a disinfectant, the shortest detention time in the system from the Intake Pump Station (IPS) to the filters will occur in the future when the pump stations and the plant are doubled in capacity. This will result in a maximum of 246,000 m³/d being pumped and treated. Table 6.3-1 shows hydraulic residence detention times (t) for the various system components, the contact time factor (T₁₀/t), where "T₁₀" is the detention time corresponding to the time for 90 percent of the water has been in contact with at least the residual disinfectant concentration "C" (AWWA, 1990), and the resultant time T₁₀, which is the time to be used in the product expression CT. From Table 6.3.1, the resulting

minimum time is 3.9 hours (234 minutes), close to the maximum times used in the nematode inactivation Test No. 2

TABLE 6.3.1
SYSTEM RESIDENCE TIMES

SYSTEM COMPONENT	HYDRAULIC RESIDENCE TIME (t) (Hr)	FACTOR F10/t	CONTACT TIME T10 (Hr)
RAW WATER PIPELINE	1.6	1	1.6
REGULATING RESERVOIR	0.5	0.8	0.4
FLOCCULATION BASIN	0.55	0.75	0.4
SEDIMENTATION BASINS	3	0.5	1.5
TOTALS	5.65	—	3.9

Therefore, it is recommended that chlorine dioxide be used because of its oxidizing benefits for taste and odor control and nematode inactivation. In addition, it should be used as the primary disinfectant, taking advantage of the long contact time available in the conveyance and treatment systems.

As the proposed primary disinfectant, the chlorine dioxide system should be sized for dosing rates capable of inactivating viruses and cysts, such as *Giardia lamblia* and *Cryptosporidium*, should future water quality conditions warrant such rates (note, however, that viruses and cysts have not been detected in the current water supply). To inactivate/remove viruses and *Giardia lamblia* cysts, the USEPA has specified 3 log (99.9%) inactivation/removal for *Giardia* and 4 log (99.99%) for viruses. A 2.5 log (99.7%) removal credit for *Giardia* and 2 log (99.0%) removal credit for viruses can be taken for an efficient treatment plant with filters. The remaining *Giardia* and virus log requirement (2 log and 0.5 log respectively) must be implemented by disinfectant inactivation (AWWA, 1990).

Appendix E shows copies of the applicable USEPA *Giardia* and virus inactivation tables for chlorine dioxide that apply to the Zai WTP raw water, i.e., pH in the 6.9 range and the worst case water temperature of 15 degrees C. From these tables, *Giardia* cyst inactivation dictates requiring a CT of 3.2 mg/L-min. With the T₁₀ time of 234 min, the residual chlorine dioxide concentration at the end of the sedimentation basins need only be 0.014 mg/L. This is the worst case condition, since at any other flows the residual can be reduced proportional to the

decrease in flow and an accompanying increase in time T_{10}

Because chlorine dioxide is a more expensive disinfectant than chlorine, its use should be limited to being the primary disinfectant. Chlorine should be added at the channel feeding settled water to the filters and again following filtration, as is the practice now, and to maintain a disinfectant residual in the distribution system.

The disinfection system, as recommended, will allow for a higher log inactivation by simply increasing the chlorine dioxide dose to provide a higher residual to meet the required CT.

There has been work done on the beneficial synergistic effects of two or more different disinfectants being applied sequentially, as recommended, i.e., chlorine dioxide followed by chlorine. Work still needs to be done on this approach to determine definitive and quantitative results for the Zai plant, however. The two proposed oxidants to be applied at the IPS, chlorine dioxide and potassium permanganate, will break down more organic molecules in the raw water than if only one were used. As discussed in the bench scale study report (Appendix C), more organic matter will be adsorbed onto the PAC in the regulating reservoir. This, together with the improved flocculation and settling performance, and the resulting reduction in chlorine demand of the oxidized and settled water, fewer disinfectant by-products, primarily THMs, will be formed in the treated water.

From the stoichiometric requirements (Equation 1, below) of combining sodium chlorite (NaClO_2) and chlorine (Cl_2) to form chlorine dioxide (ClO_2), 1 part of Cl_2 is required for every 2.68 parts of NaClO_2 , assuming 95 percent efficiency.



From Test No. 2 of Appendix C, the reduction of ClO_2 in the simulated conveyance time averaged 47 percent for doses greater than 1 mg/L. Theoretically then, only 0.03 mg/L of chlorine dioxide is needed. Practically, it is recommended that provision be made for a higher dose, on the order of 3.0 mg/L installed capacity, assuming a 1.5 mg/L average dose. Operational experience will determine if this average dose can be reduced any, taking into account the relative cost compared with both KMnO_4 and PAC. This high dose will not be necessary to meet disinfection requirements, however, as pointed out earlier.

Chlorine dioxide is a powerful oxidant and excellent disinfectant (AWWA, 1997 and Cooper, 1981). Its use is growing in a number of areas, including the U.S. and Western Europe. The reason for the rising interest in and use of this alternative disinfectant in the U.S. is two-fold: (1), the disinfectant by-product THM is minimal, and (2), the USEPA proposes, in its next round of regulations, less stringent ClO_2 by-product maximum contaminant levels (MCLs), i.e., 1 mg/L of chlorite ion only (Pontius, 1998). Previous suggested MCLs for chlorite, chlorate, and the ClO_2 residual levels themselves, were much more stringent, making the use of chlorine dioxide problematic.

Chlorine dioxide as a gas is dangerous and potentially explosive, and it must be generated at the site where it is to be used. ClO_2 for use in water treatment is made from by mixing chlorine and sodium chlorite. The early generator designs involved pumping a solution of sodium chlorite into a solution of chlorine. However, 2 to 3 times the amount of chlorine

required stoichiometrically was needed by the process. High levels of THMs also resulted from this method. Modifications to this type of generator system were made, such as adding an acid and optimizing the mg/L Cl_2 in the Cl_2 solution, thereby reducing the excess Cl_2 .

A more recent alternative generator has been developed that blends a chlorine gas and sodium chlorite solution and yields a greater than 95 percent chlorine dioxide solution with less than 5 percent excess chlorine (AWWA, 1997). Figure 6-3-1 shows a schematic diagram of this type of generator, which is recommended for use at the IPS. Appendix D provides a copy of a manufacturer's catalog featuring this type of generating system. Figure 6-3-2 is a plan of the chemical building needed at the IPS to house the equipment for the chlorine dioxide and potassium permanganate systems, and areas for chemical storage.

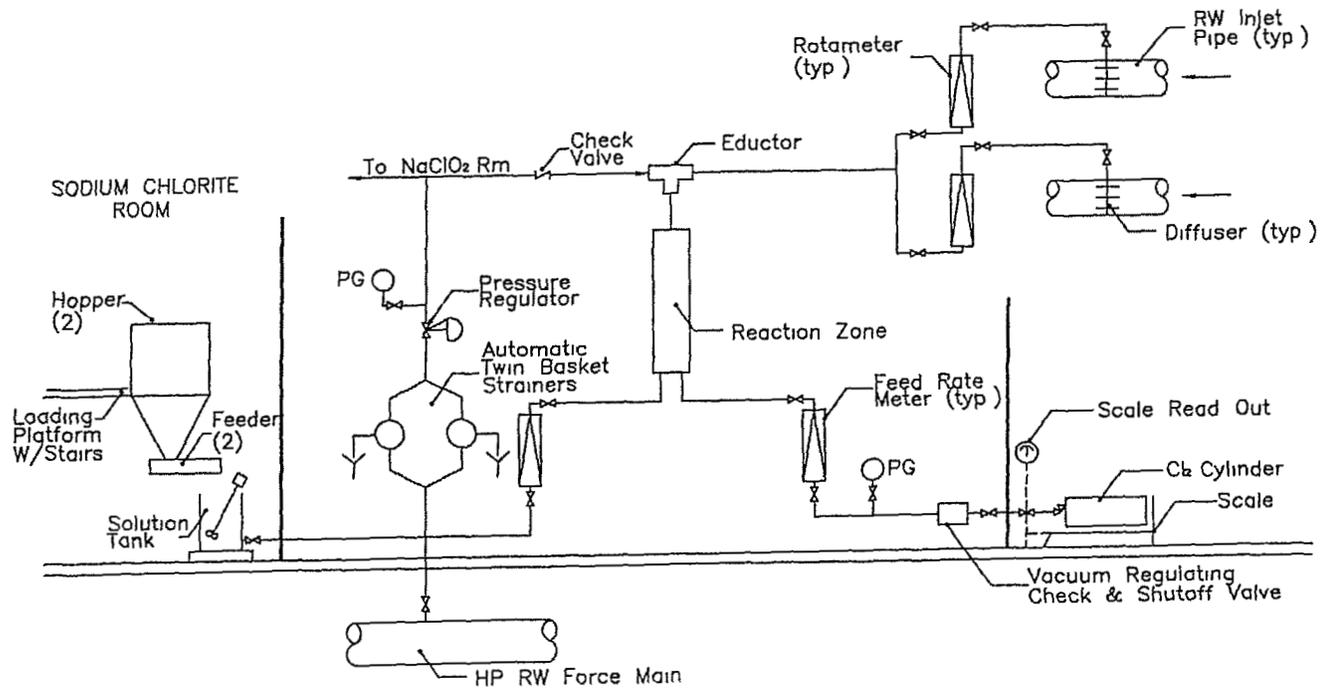
A positive way to inactivate nematodes is to use ozone as the primary disinfectant. However, unless there is justification for the use of ozone for other compelling reasons, its use in this application cannot be economically justified. Ozone is the strongest disinfectant available and does not form THMs. The capital cost of an ozone system to supply 3 mg/L of ozone and contactors designed for a contact time of 12 minutes is estimated at JD 3,200,000. The operating cost of such a system, assuming air feed with all the associated air filtering and drying equipment, would amount to JD 4,000 per day at 123,000 m^3/d . CDM does not recommend an ozone facility for the Zai WTP at this time.

Other disinfectants such as chloramine, a compound made from chlorine and ammonia, and chlorine dioxide, produce only minimal quantities of THMs. These disinfectants will form other disinfectant by-products, but in small enough quantities not to cause health problems, (based on current knowledge), and are much less costly than ozone.

6.4 Raw Water Regulating Reservoir

This regulating reservoir acts to balance the water being delivered to the Zai WTP from the pumped raw water conveyance system and the rate of water treatment at any particular time. Upstream of the reservoir a vault is located over and around the incoming raw water force main with provision to add caustic soda (never used), powdered activated carbon (PAC), and potassium permanganate. Currently, potassium permanganate and chlorine are being added at this point. PAC is being added at the first rapid mixer together with the alum coagulant. This is not an optimum arrangement. PAC should be added to raw water for taste and odor removal well before a coagulant is added. This provides time to allow the PAC to adsorb the taste and odor compounds in the raw water before coagulation. This will have the added benefit of reducing THM formation, since more time is provided for organic precursors to be adsorbed. CDM has designed many PAC contact basins with success, as well. Ideally, PAC should be added to the raw water at the Intake Pump Station, since this would allow the longest possible contact time. However, PAC is very abrasive and would do damage to the pump impellers along the conveyance system. An alternative would be to add it to the raw water on the discharge side of the Pump Station No. 4. This would necessitate using very high pressure PAC slurry metering pumps, however.

If PAC and alum are added together, as is now practiced, the PAC particles become nuclei for floc formation. That means the carbon particles become coated with alum floc before the carbon can adsorb the taste and odor compounds, thus minimizing its effectiveness. The best



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CHLORINE GAS-SODIUM CHLORITE SOLUTION
SYSTEM SCHEMATIC

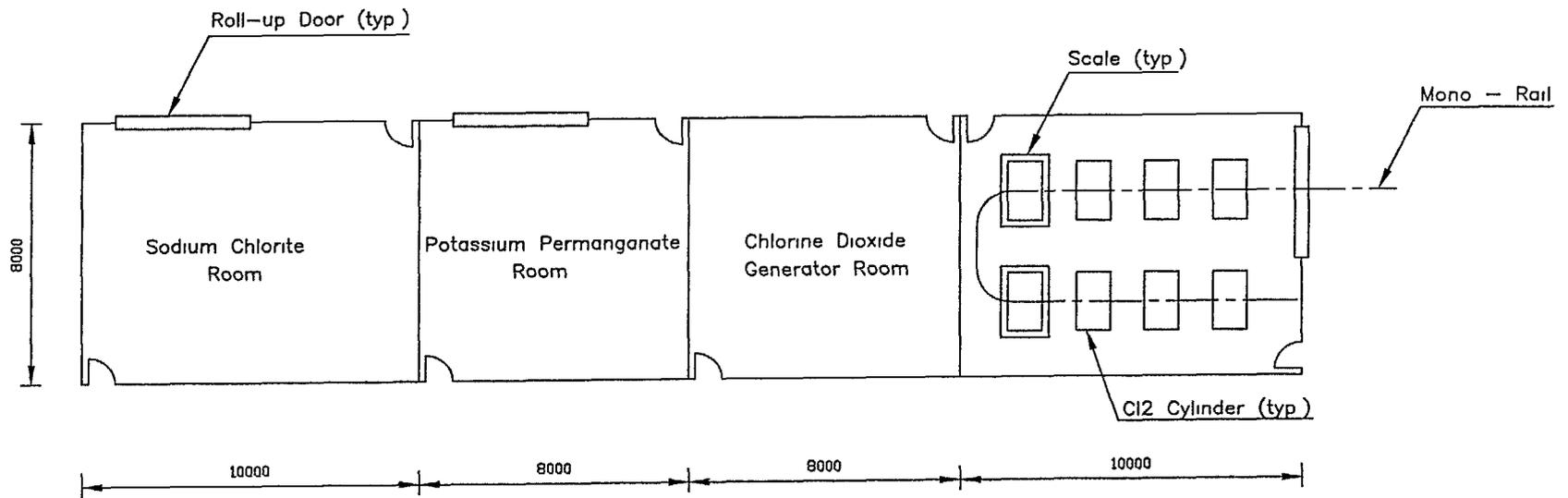
Figure 6 3-1

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ZAI WTP

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Zai



PLAN

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CDM Camp Dresser & McKee International Inc

INTAKE PUMP STATION
CHEMICAL BUILDING PLAN

Figure 6 3-2

ZAI WTP

NOV 98

economic solution is to utilize the existing regulating reservoir as contact basins for PAC taste and odor control by adding the PAC to the raw water at the existing chemical injection vault. Baffling both compartments of the reservoir will minimize short-circuiting and maximize the detention time and contact times for the carbon and minimize carbon deposition. The current way of using the reservoir is to pass the water through the two compartments of the reservoir in series. Water passes from the first into the second over the intermediate dividing wall. This means only the one compartment can be used for baffling. And particle deposition will occur in the outer ends of each compartment. This limits the regulating capacity of the reservoir. When the plant is doubled in capacity, baffling will not be possible. The Japanese engineers who are designing the plant expansion have assumed the full capacity of the reservoir for regulating purposes in their design.

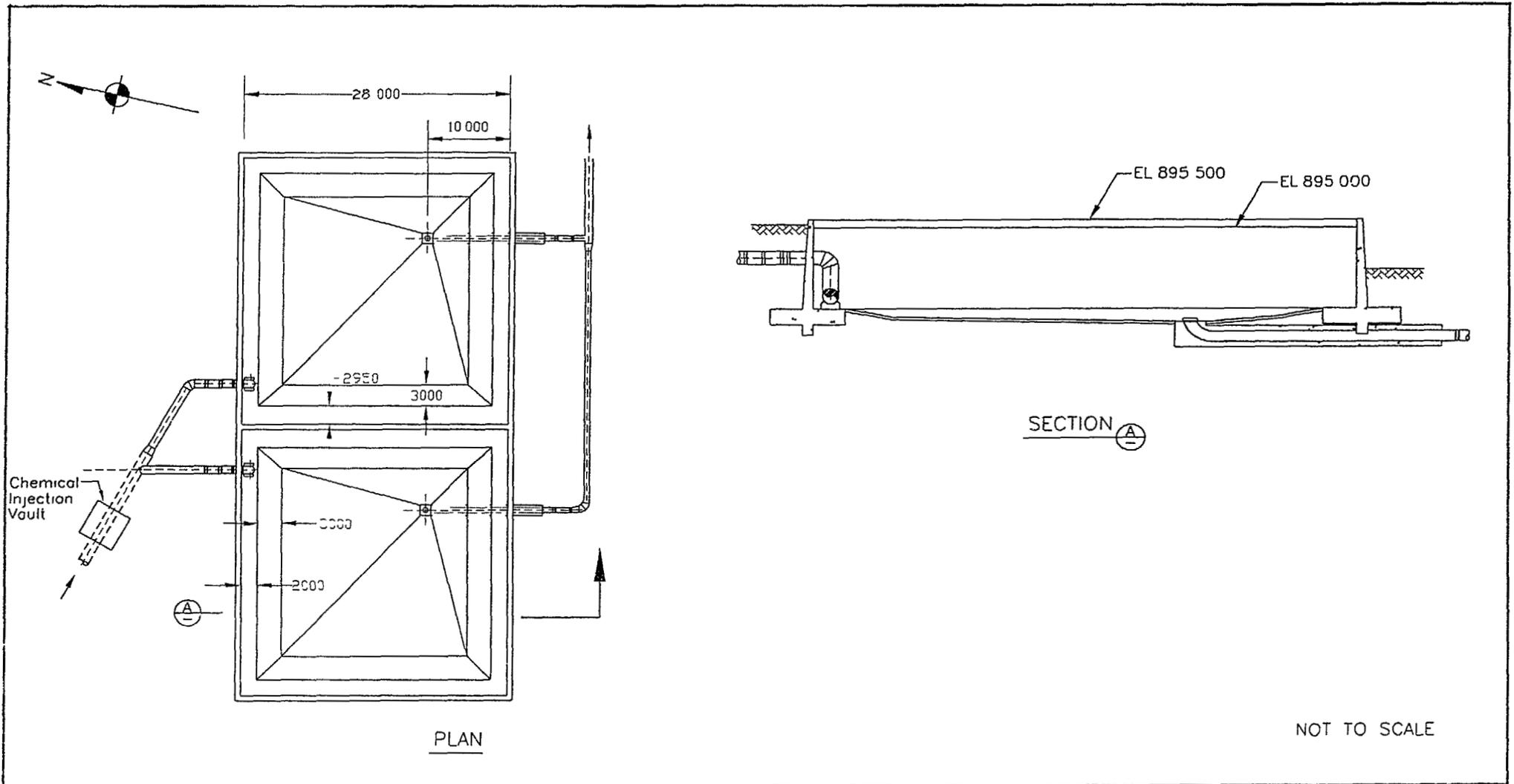
Chlorine addition at the raw water regulating reservoir application point should be stopped when PAC application is started there, since PAC will adsorb the chlorine and nullify its residual effect. Instead, chlorine should be applied at the settled water channel, just ahead of the filters.

Figures 6-4-1, 6-4-2, and 6-4-3 show the configuration of the existing and recommended reservoir baffling arrangement and baffle details. As stated above, potassium permanganate should be added at the Intake Pump Station. The added PAC contact time through the regulating reservoir will improve the effectiveness of PAC for organic adsorption, and therefore reduce the formation potential for THMs when chlorine is finally added.

The baffling configuration, as proposed, will not only minimize short-circuiting in the reservoir compartments but minimize particle deposition. The velocity in the rice-ways of the baffled compartments will be 0.04 meters per second (m/s) at 123,000 m³/d plant flow and both compartments at maximum water level. This is compared to 0.01 m/s in the sedimentation basins. The reservoir velocity will increase to 0.08 m/s when the plant is doubled in capacity. It is possible that some PAC may drop out at times, but it will be a simple matter to move this deposited material out. For example, all the incoming raw water can be passed through one compartment for a short time and operated at whatever depth will be needed to provide the necessary added velocity to move deposited material. Similarly, both compartments could be operated together and the water levels dropped to increase the velocity for a short time. No manual cleaning will be necessary, except for the normal annual close down and inspection of one compartment at a time. The design details of the hypalon baffles include sand-filled hems at the bottoms to keep the baffles on the floor and prevent short-circuiting.

6.5 Rapid Mixing

The existing rapid mixing system consists of two vertical turbine, mechanical, electric motor-driven mixers in series. The arrangement is not efficient and the coagulant cannot be mixed quickly enough into the water. Back mixing and short-circuiting through the basins also occurs. Ideally, the quicker the coagulant chemical can be added to the water the more efficient the use of the chemical and the less chemical is needed. CDM's experience has been that up to 20 percent less coagulant is needed if the coagulant is mixed into the water quickly. This has been verified by others also (Kawamura, 1991). The hydraulics of the plant is such that excess head between the water level in the regulating reservoir and the top water level in



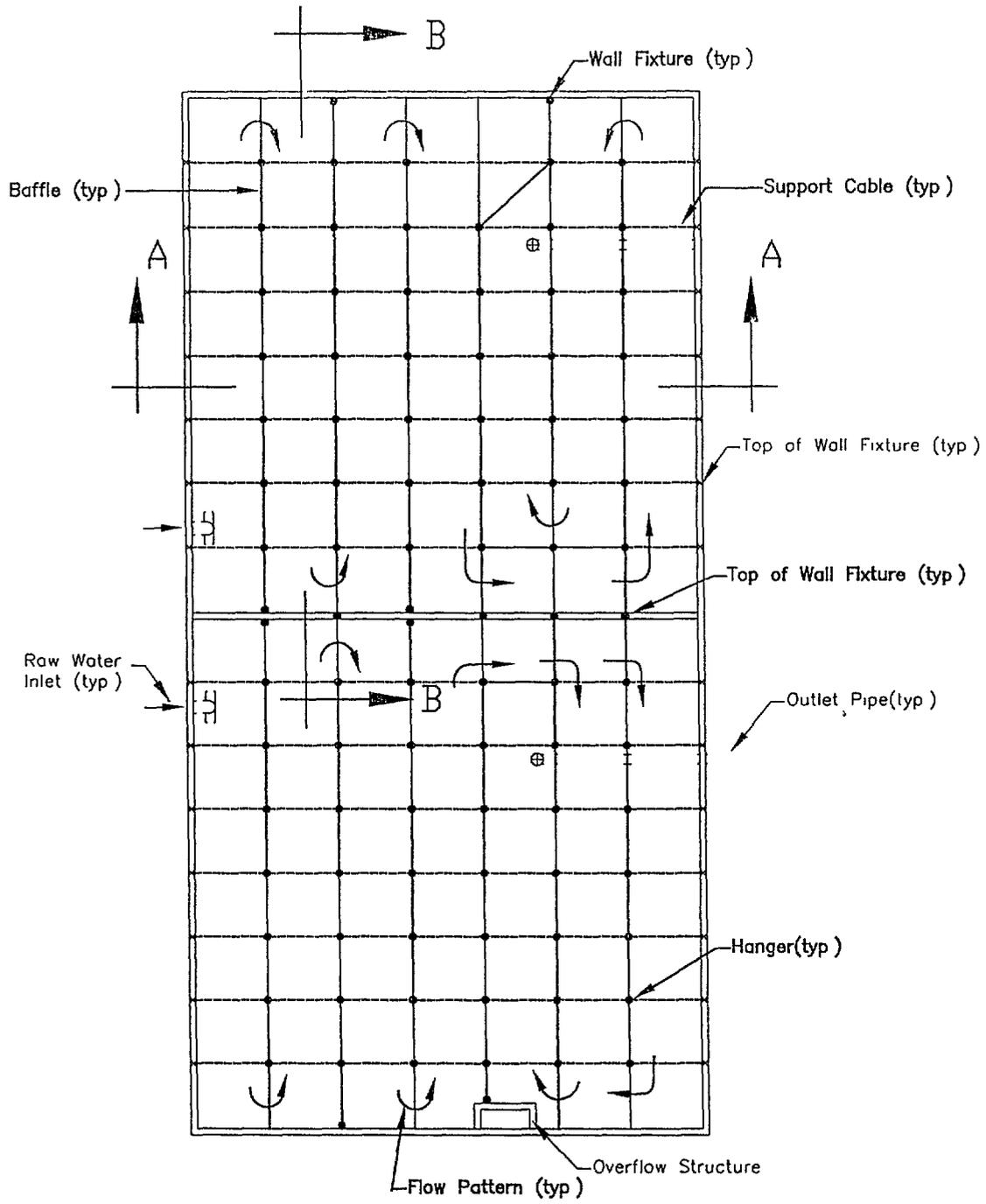
CDM Camp Dresser & McKee International Inc

EXISTING RAW WATER REGULATING RESERVOIR

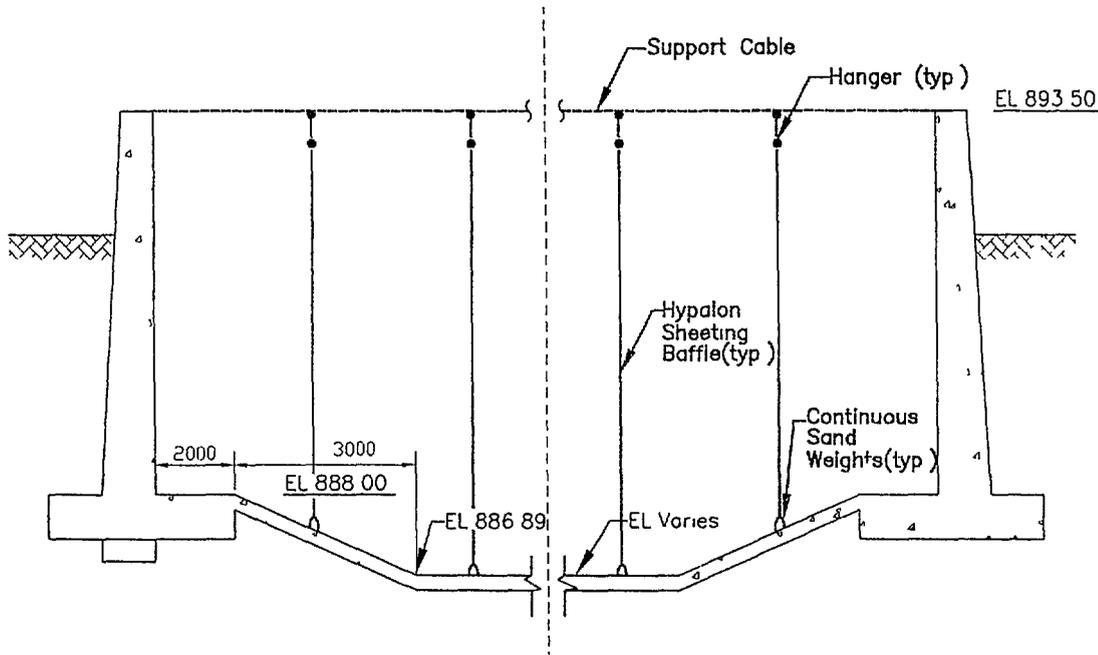
Figure 6 4-1

ZAI WTP

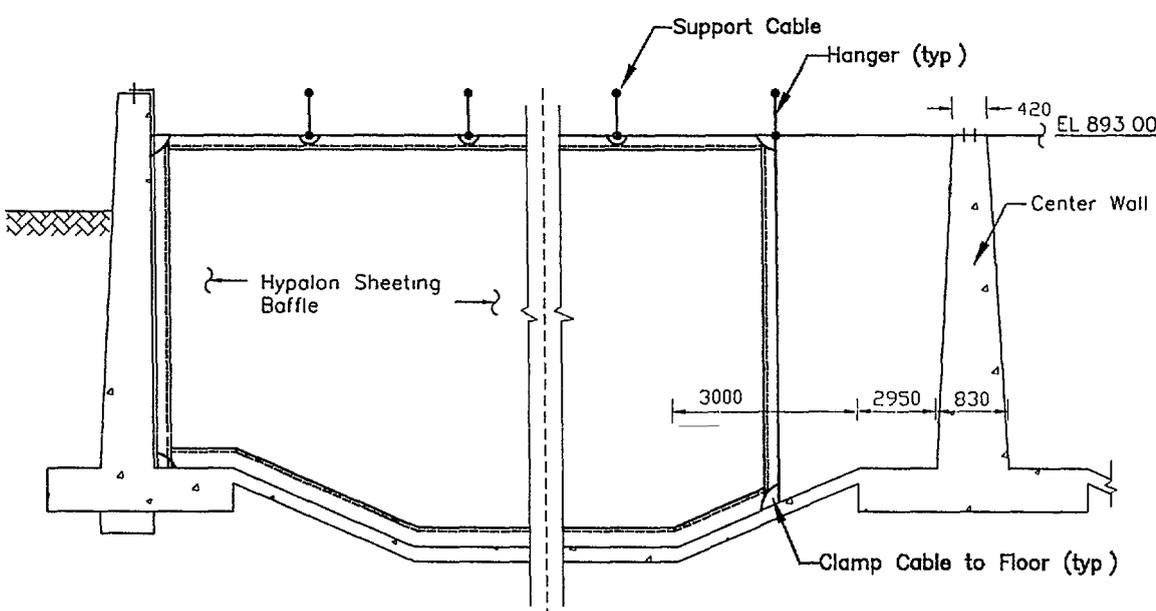
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SECTION A-A



SECTION B-B

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the rapid mixing basin has to be dissipated through the raw water flow control modulating butterfly valve, as seen by the hydraulic profile shown in Figure 6.5.1. It would be more economical to modify the current system to provide flash (close to instantaneous) mixing, using some of the excess head available, either by using a weir configuration or a pressure jet and splash plate. The pressure jet/splash plate hydraulic mixing method has been used successfully for many years by British designers. This way, the concept of flash mixing and chemical reduction will be realized and the cost of running and maintaining the mixer will be eliminated. The existing rapid mixers should be removed. The nozzle for the replacement system would be designed to accommodate all flow ranges.

The flash mixing concept is not needed for the polymer coagulant aid. Again, using some of the excess available head, hydraulic mixing using baffles would be adequate, and the mechanical mixer could be eliminated. Figures 6.5.2 and 6.5.3 show the existing mechanical flash mixing arrangement for the coagulant and the polymer coagulant aid. Figures 6.5.4, 6.5.5, 6.5.6, and 6.5.7 show the alternative arrangements. These are simple configurations that will cost very little to implement but will yield long term savings. Of the two alternatives developed, CDM recommends the nozzle type of flash mixing. As stated above, it is recommended the PAC application point be relocated from the first flash mixer to the raw water pipe vault upstream of the regulating reservoir.

6.6 Chemical Coagulation

The plant was designed for the use of aluminum sulfate (alum) as the primary coagulant. This has worked satisfactorily, although due to the relatively high pH of the raw water, excessive alum is perhaps being used to lower the pH closer to the optimum value for coagulation. However, with the advent of the knowledge of nematodes in the raw water, it is advisable to increase efforts to ensure their removal at the plant so that they do not get into the distribution system, dead or alive. The use of an alternative coagulant should be considered so as to form a better and heavier floc to ensure more effective floc and particle removal in the sedimentation basins and less load on the filters. The two possible candidates are ferric sulfate and ferric chloride. The former is more economical, as it is available in a dry form and is compatible with the existing corrosive resistant alum equipment now in use at the plant. Another advantage of using a ferric salt as a coagulant is that the resulting sludge dries better than for an alum sludge. It will also be advisable to identify alternative heavy molecular weight coagulant aid polymers for the same reasons, to form a heavier floc. Investigations should be made and tests conducted to identify a polymer more compatible to ferric coagulants than the polymer currently being used as an alum coagulant aid. The pH of the raw water is more optimum for a ferric salt coagulant, and its use should result in less coagulant being required. CDM is therefore recommending the use of ferric sulfate as the primary coagulant in place of alum. CDM believes this option to be a better alternative than lowering the pH by adding an acid, as recommended by Dr. Christoph Czeka, the German consultant that reviewed the Zai WTP and its operation. Jar tests were conducted to compare the relative effectiveness and costs of alum, ferric sulfate, and ferric chloride. The testing procedure is included in Appendix C.

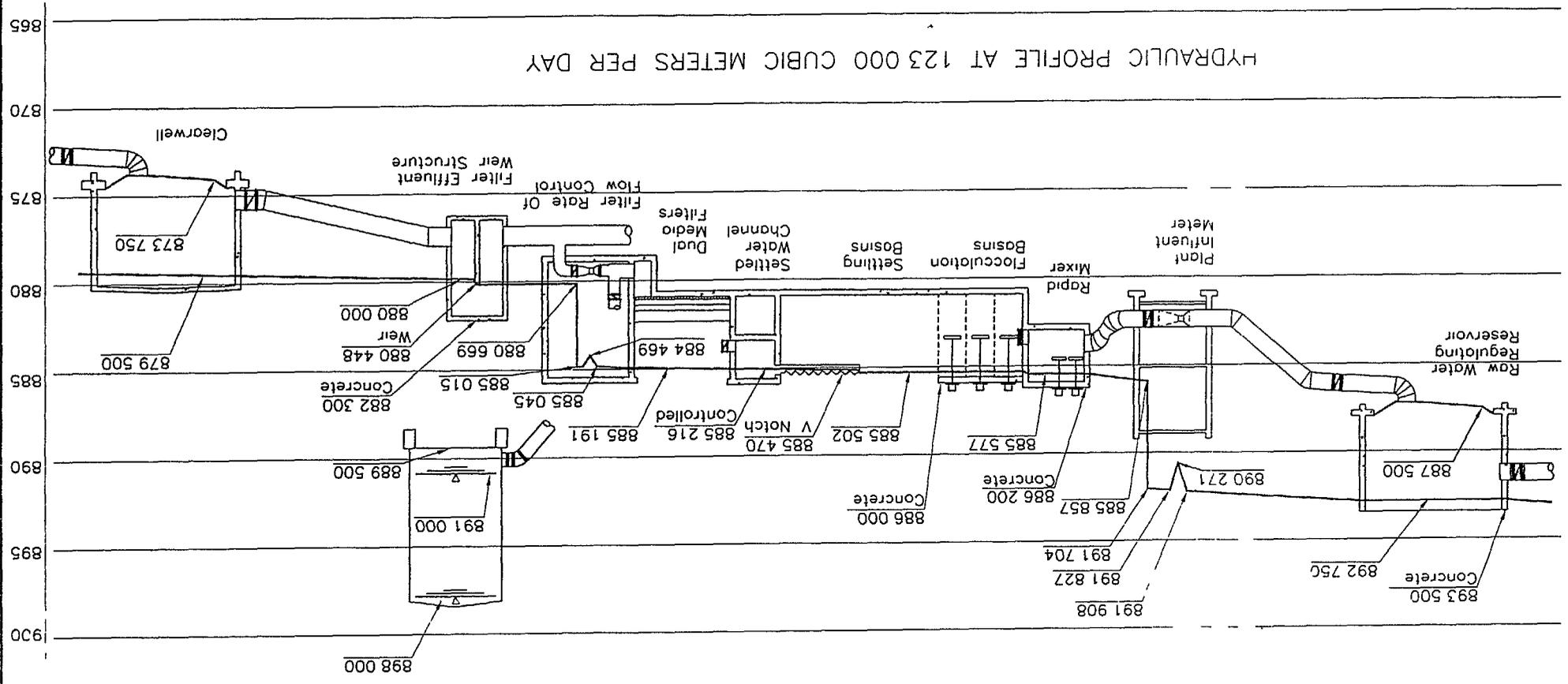
From these limited tests, the ferric salts proved effective. Ferric chloride was somewhat better than ferric sulfate. It did however, depress the pH more and final pH adjustment with a base would be needed. Ferric chloride is also a more corrosive metal salt than ferric sulfate.

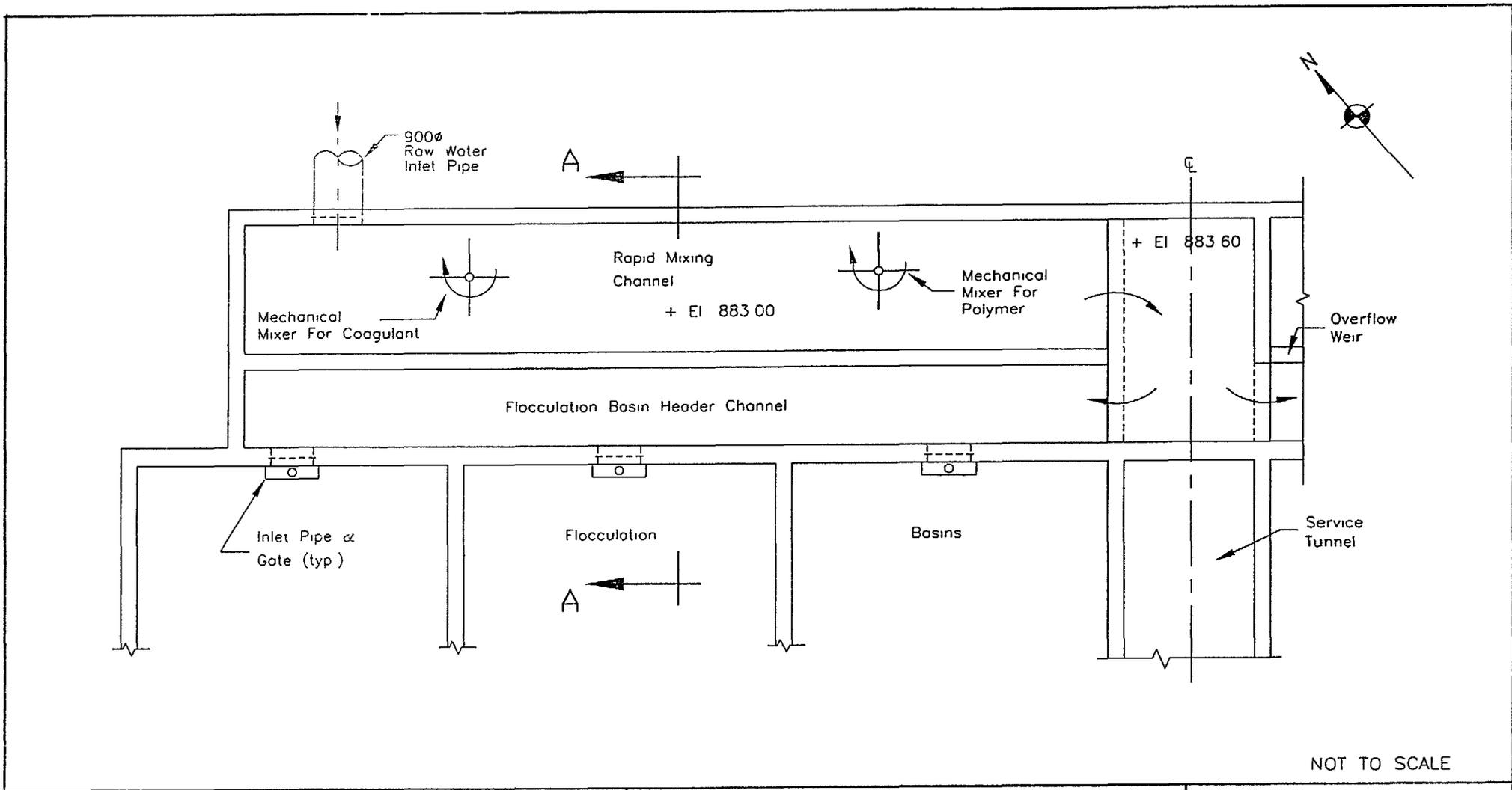
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HYDRAULIC PROFILE

Figure 6 5-1

HYDRAULIC PROFILE AT 123 000 CUBIC METERS PER DAY

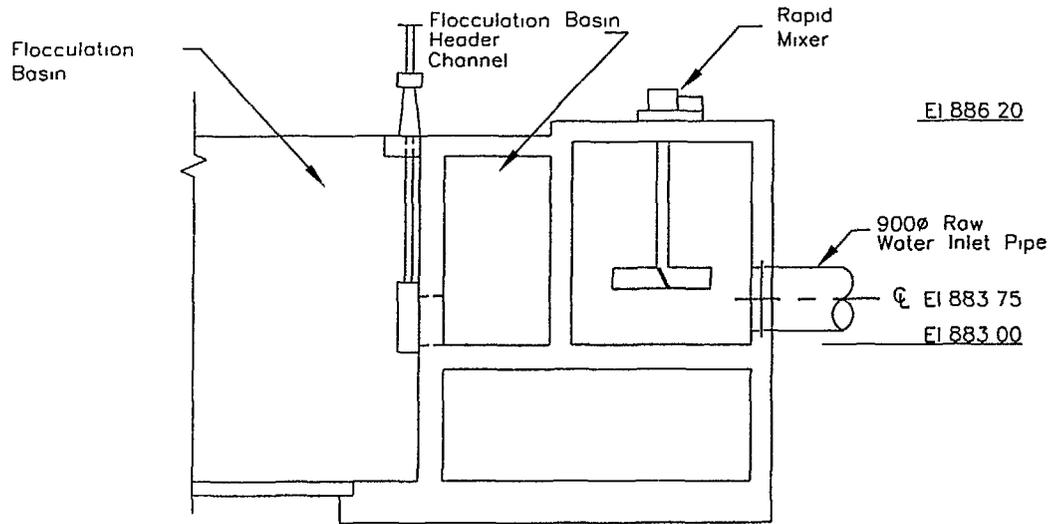




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CDM Camp Dresser & McKee International Inc	EXISTING RAPID MIXERS	Figure 6 5-2
	ZAI WTP	NOV 98

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SECTION A-A

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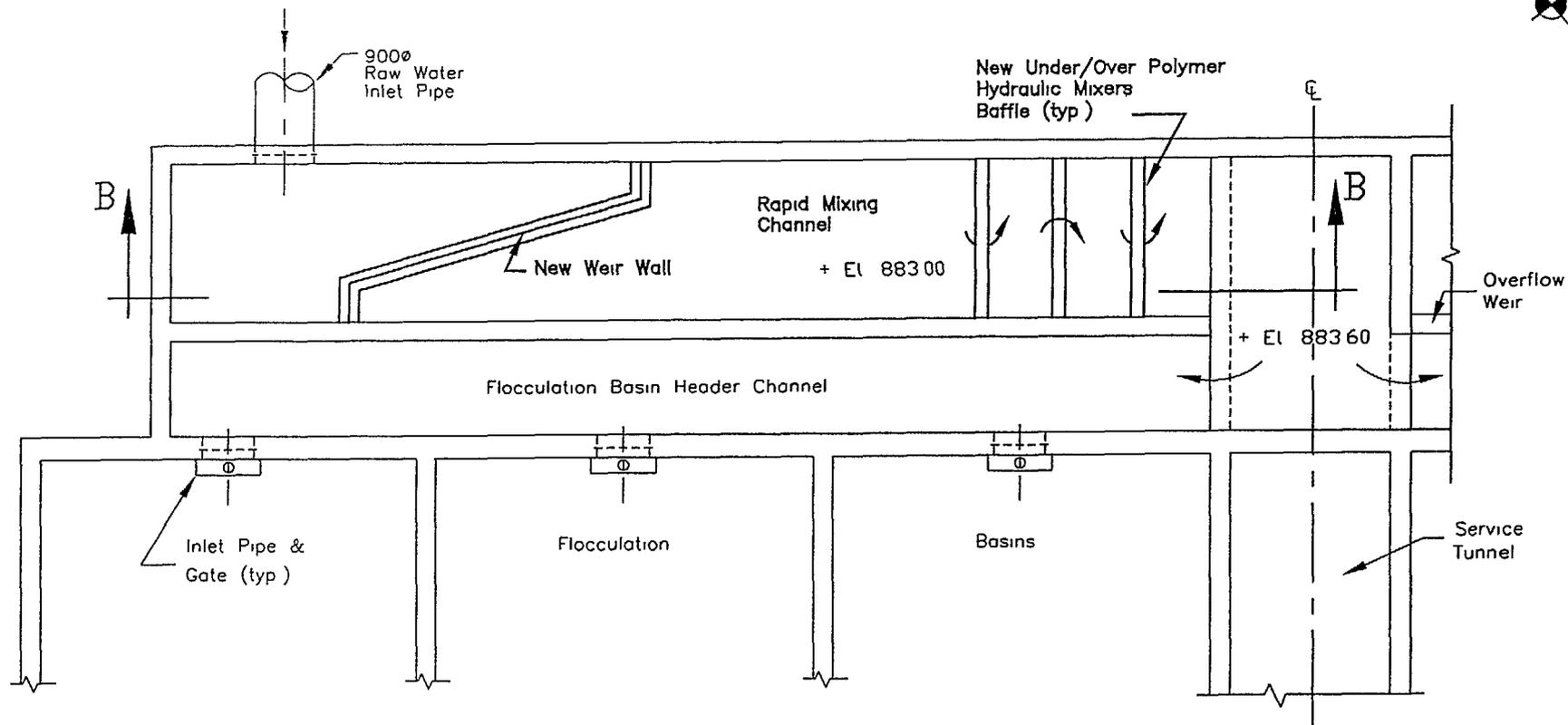
CDM Camp Dresser & McKee International Inc

EXISTING RAPID MIXERS
(SECTION A-A)

Figure 6 5-3

ZAI WTP

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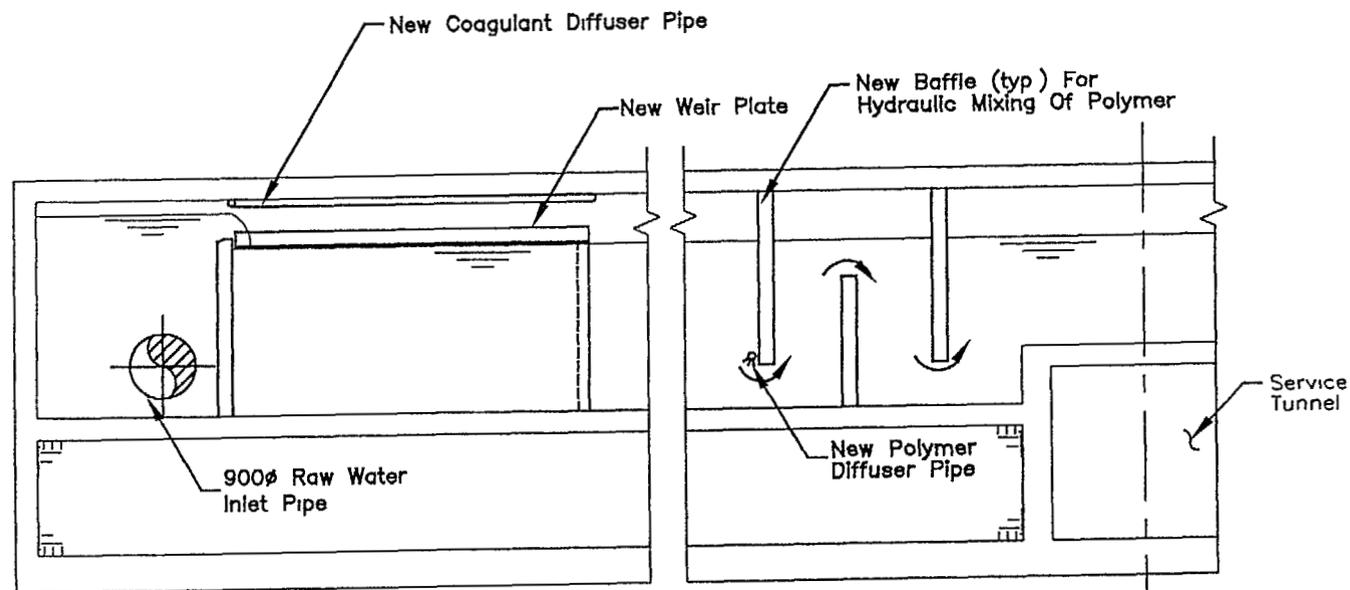
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HYDRAULIC MIXING WEIR ALTERNATIVE

Figure 6 5-4

ZAI WTP

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SECTION B-B

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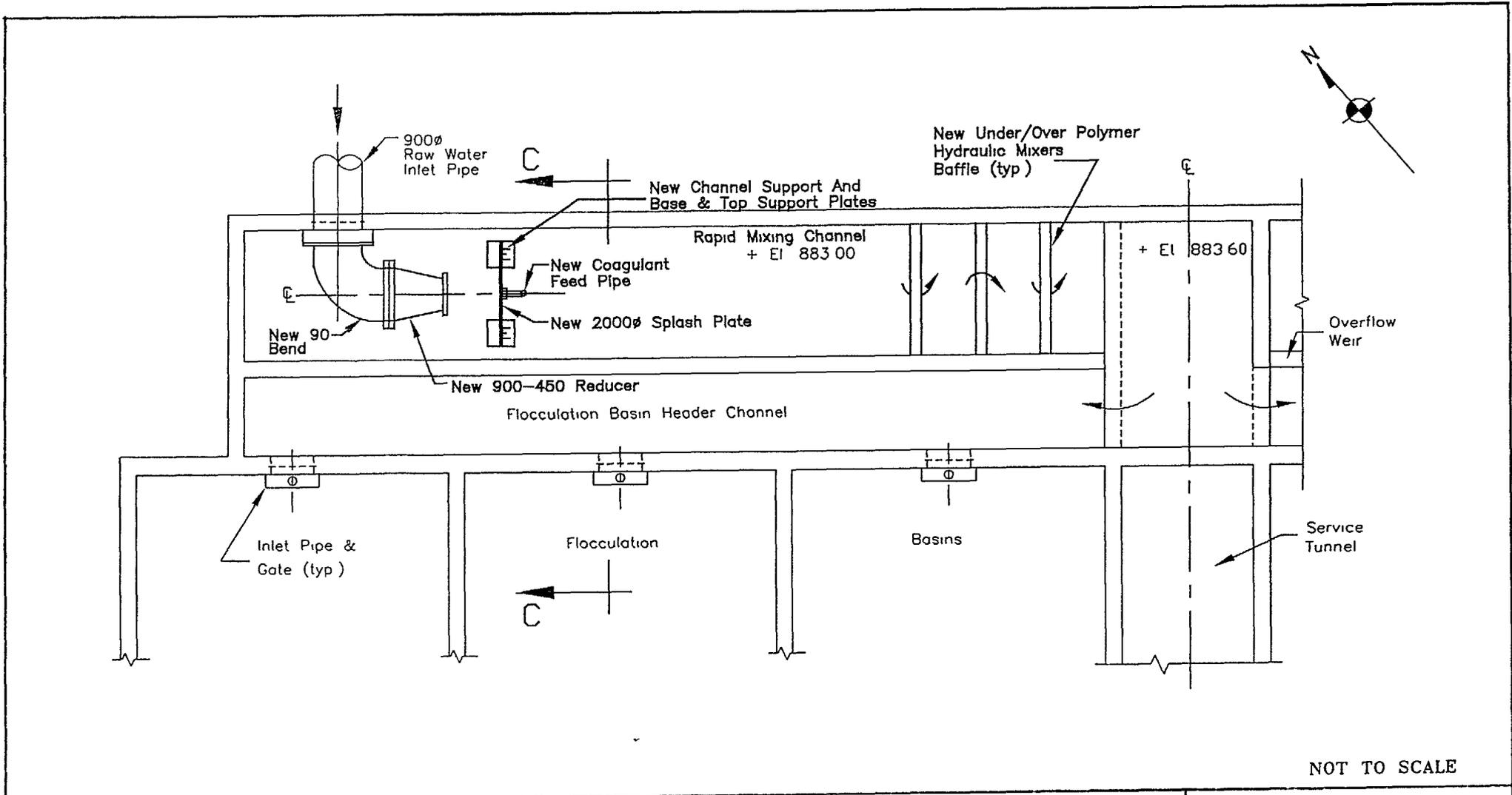
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HYDRAULIC MIXING WEIR ALTERNATIVE
(SECTION B-B)

Figure 6 5-5

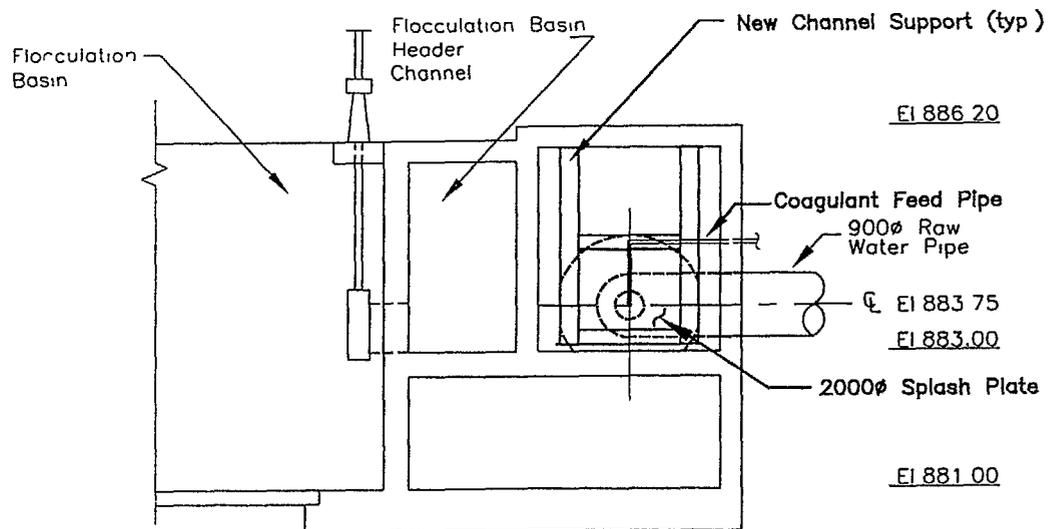
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CDM Camp Dresser & McKee International Inc	HYDRAULIC MIXING NOZZLE ALTERNATIVE	Figure 6 5-6
	ZAI WTP	NOV 98



SECTION C-C

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CDM Camp Dresser & McKee International Inc	HYDRAULIC MIXING NOZZLE ALTERNATIVE (SECTION C-C)	Figure 6 5-7
	ZAI WTP	NOV 98

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Therefore, if it were used all the existing alum feeders and pumps would have to be replaced with equipment made from more corrosive resistant materials. If ferric sulfate is used, the existing alum equipment could be used. CDM recommends ferric sulfate over alum because they produce a heavier floc than alum floc. This will result in better particle separation and nematode removal and avoid aluminum residual and carry over into the distribution system. CDM recommends ferric sulfate over ferric chloride because it is less corrosive, new feeder and pump equipment will not be needed, and pH adjustment will not be necessary. A further benefit of using ferric sulfate is that less sludge will be produced. This will have less environmental impact, compared to the large volumes of alum sludges currently produced at the plant. Section 10 includes all the relevant cost comparisons between the alum and ferric sulfate systems.

6.7 Flocculation Basins

The flocculation system is a good design with two trains, each train having three parallel flocculators with three stages in series. The flocculators are the mechanical vertical turbine type, with two speed electric motor drives. There are therefore, a total of nine flocculators per train. There are two parallel trains, each with three flocculators per stage, with baffled walls between each stage, making a total of 18 flocculators. The velocity gradients for each stage are 100^1 , 80^1 , and 60^1 at the higher speed. This arrangement, together with the vertical turbine type mixing, ensures minimum short circuiting and good detention times for floc to form. Currently, the first stage flocculators are operating at their high speed while the second and third stages are operating at their low speeds. It may be more effective to operate all flocculator drives at their lower speeds. This should result in a marginally larger floc and will reduce the wear and maintenance costs and the current draw on the six first stage flocculator drives. In order to further improve the flow through characteristics of the flocculation basins, it is recommended that perforated walls be installed at the first or inlet stage of the flocculators. Currently, there is a single inlet pipe to each basin. A perforated inlet wall will tend to reduce short circuiting in the first stage. Figures 6.7-1 and 6.7-2 show the recommended wall location. The provision to add a flocculant polymer aid has been added recently. The polymer is currently being added to the top of the water at the start of the third stage of flocculation. This is not an efficient application point. CDM recommends the piping be rerouted to allow for the injection of the polymer directly under the flocculator impellers. To add flexibility, provision should also be made to provide the option of adding the polymer under the second stage flocculator impellers. Full scale plant testing will quickly identify, for different types of polymer, which application point is better based upon floc formation, size, and polymer cost.

6.8 Sedimentation Basins

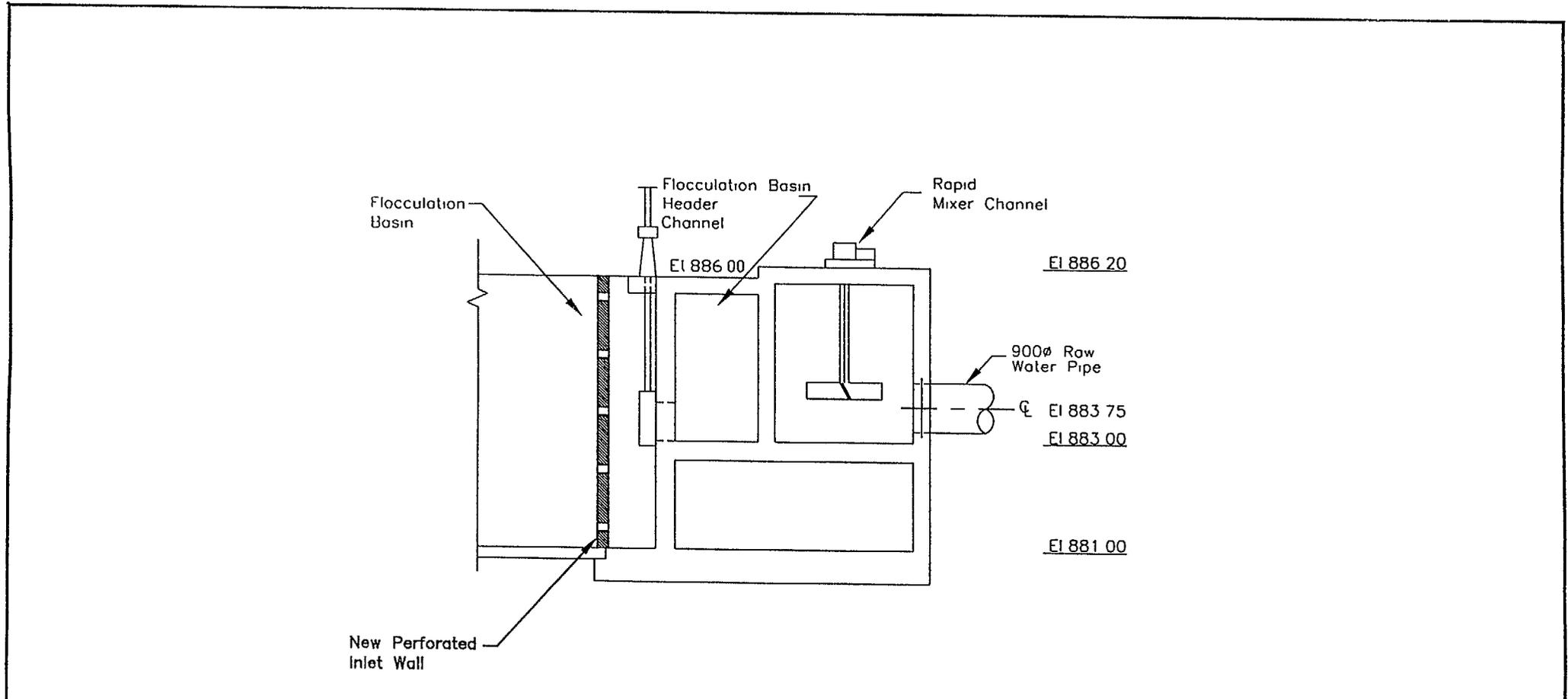
There are two sedimentation basin trains in parallel, matching the flocculation trains. Flocculated water enters the basins directly from the flocculation basins through perforated dividing walls. At the design capacity of $61,500 \text{ m}^3/\text{d}$ per train, the overflow loading rate is 1.5 m/hr . Settled sludge is vacuumed off the bottom by a travelling bridge type scraper mechanism, using suction pumps mounted on the bridges. The track records of these types of scrapers have not been good in the United States. They tend to rack and jam. However, the operators report the units at the Zai WTP do not cause problems. Therefore, there is no recommendation to change these out with an alternative system.

The sedimentation basins have long finger launders and weirs. This type of design results in a large outlet zone and an extensive associated dead zone. This configuration results in some short-circuiting and is therefore inefficient, considering the size of the basins. Figure 6 8-1 displays a plan and section down the length of a basin, showing the theoretical flow pattern through the existing basin and settling path of a discrete particle. If the wind is flowing down the length of the basin in the opposite direction from the flow, circulation flows can result. By eliminating the finger launders and weirs, and adding a perforated baffle wall at the outlet end of the basins, the settling zone can be increased by close to 50%. This will result in smaller floc settling out in the basins at the same flow-through rates. Figure 6 8 2 shows the possible theoretical settling path of discrete particles under this scenario. The actual floc settling path will be better than the discrete particle path shown, because floc will agglomerate as they settle and collide with other floc on the way down. Using a ferric salt and/or heavy molecular flocculant aid polymer will give even better results. Comparing this Figure 6 8 2 with Figure 6 8-1 demonstrates graphically the potentially better performance of basins with the finger launders removed and a perforated end wall added. Isolation sluice gates can be added at each existing wall opening where the launders meet the wall. Alternatively, these openings can be blocked up, two larger openings cut, and sluice gates added. CDM has retrofitted many sedimentation basins in the United States in this manner, with marked improvement to floc separation.

It will not be necessary to demolish the full launders and their support columns. Only the short pieces of launder between the first columns and the end wall need be demolished. A hole should be cored into the outer end of the launders to allow some flow through the launders to prevent local stagnation. Currently, there is provision for adding PAC to the settled water at each launder. Whereas this application point is not currently being used or has never been used, it is not recommended, as PAC can migrate right through the filters. Further, PAC will inactivate the pre-chlorine being added to the help keep the filters clean from aquatic growths and nematodes.

6 9 Filters

There are six dual-media filters, each with 600 mm of anthracite over 300 mm of sand supported by a 300 mm of multi layered gravel. The underdrains are the perforated plastic block type. The filters are each divided into two cells with a central filtered water gullet under a feed channel. The filters are fitted with waste wash water troughs. Water for backwashing is pumped from the filter control weir chamber to a backwash water tank. Backwash water is fed to the underdrains from a header pipe via the filtered water gullet. The rate is controlled by means of a rate-of flow controller consisting of a venturi meter and a modulating, motor operated, butterfly valve. An auxiliary rotating surface water wash is included. This type of system does not reach large areas in the corners of the filters surfaces. The filters are washed every 24 hours or less based upon terminal head loss or time, whichever comes first. Each filter is fitted with a turbidimeter. These may not be working properly, as the readings appear to be unreasonably low. The individual filter turbidimeter readings are not transmitted to the control room or tied into the control loop. Nematodes were reported by the German consultant to be accumulating in and passing through the filter media, although no live nematodes have been known to leave the plant. Also, the backwash system does not clean the media as well as it should. The filters have all been cleaned recently.

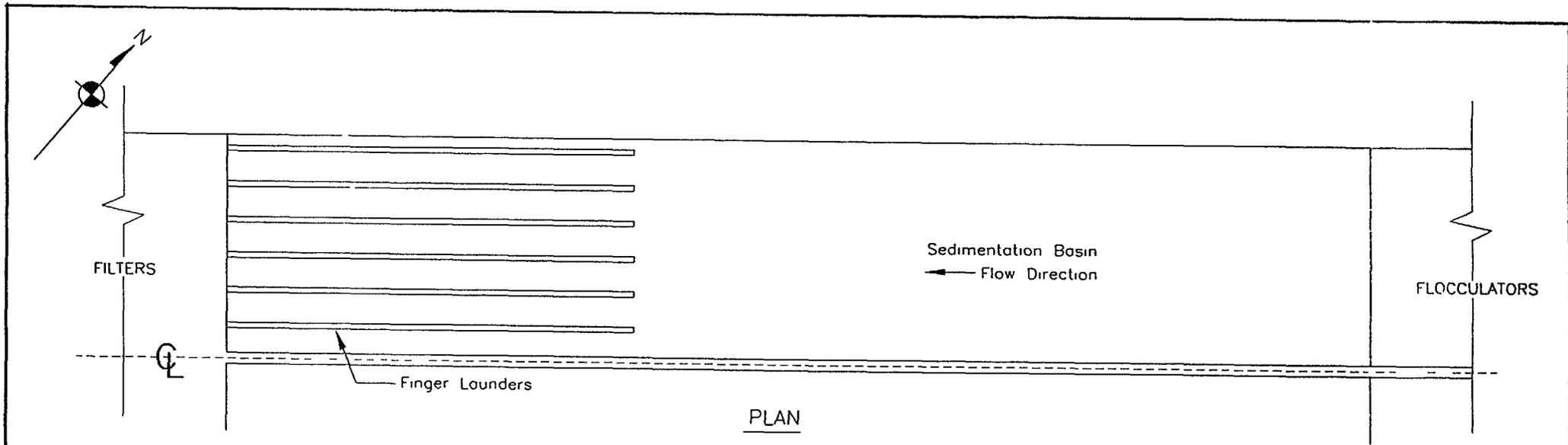


SECTION D-D

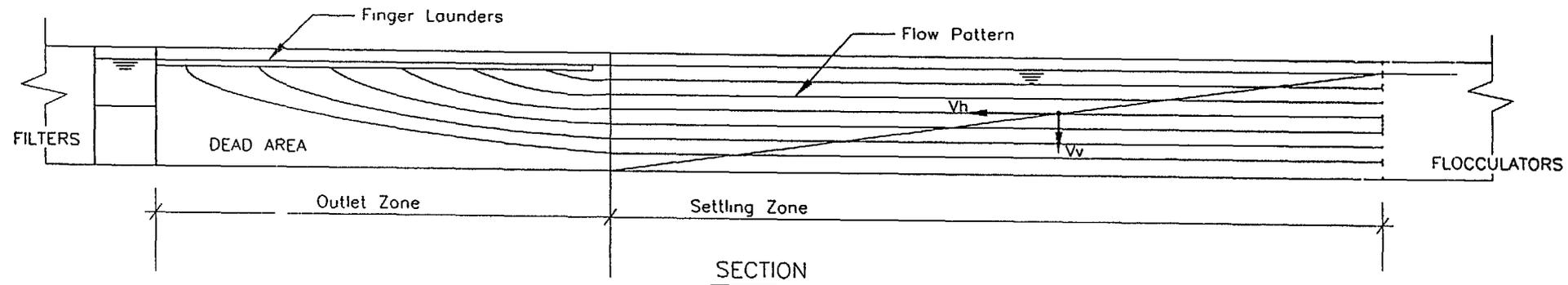
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CDM Camp Dresser & McKee International Inc	FLOCCULATION BASINS INLET BAFFLE WALL (SECTION D-D)	Figure 6 7-2
	ZAI WTP	NOV 98

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PLAN



SECTION

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EXISTING SEDIMENTATION BASINS

Figure 6 8-1

ZAI WTP

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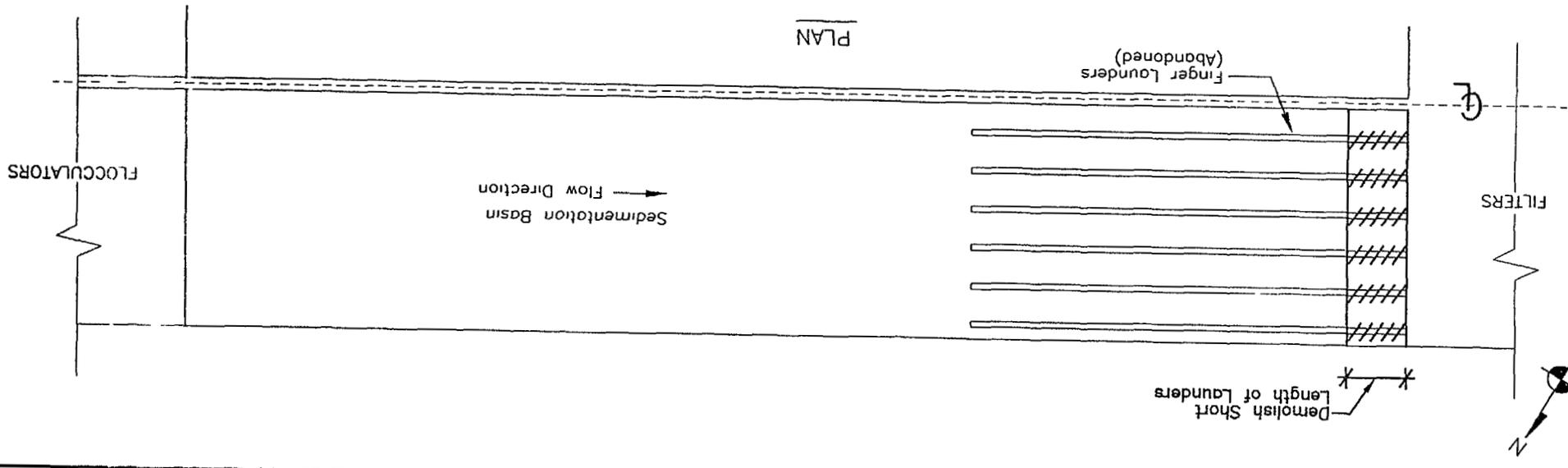
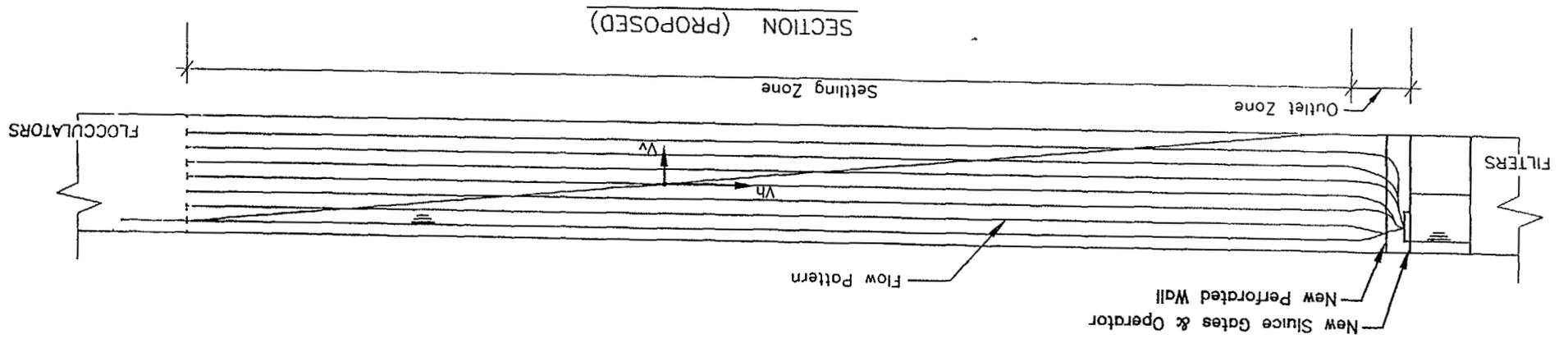
MODIFIED SEDIMENTATION BASINS

ZAI WTP

NOV 98

Figure 6-8-2

NOT TO SCALE



by a mixture of chlorine and sodium hydroxide (caustic soda) in order to remove coagulant floc, mud deposits, and nematodes

To more effectively clean the filter media, and ensure nematodes are not breeding in the media, CDM recommends that the filters be fitted with an air scour system in place of the existing surface water wash. Water backwashing alone will not effectively clean media, this is particularly true when a filter aid is used (Monk, 1987). A combined air and water backwash system will ensure that the full depth of the media is effectively cleaned. The use of concurrent air scour and water in backwashing is virtually standard practice in the USA and Europe. CDM has designed all of its filters since the 1970s with air scour systems.

The wash cycle of an air water backwashing system is no longer than a water surface and water backwash system. There are air scour systems available that comprise a grid system that can be installed in place without removing the media. The installation is achieved while the media is fluidized. In order to ensure that the floc carried over onto the filters from the sedimentation basins is trapped in the filters, it is recommended that provision be made for a nonionic polymer to be added to the settled water.

It is further recommended that provision be made to eliminate turbidity spikes in the filtered water at start up following a backwash. This can be done by including in the backwash system provision to add a polymer to the backwash water during the last few minutes of the water backwash, allowing for starting the backwashed filter slowly, allowing the filters to rest for up to an hour before being brought back on line following a backwash, or any combination of these techniques. The automatic backwash sequence should be initiated on a preselected terminal turbidity, terminal head loss, or terminal filter run time, whichever comes first. This concept should be incorporated into the expansion and control modifications proposed by the Japanese.

The air scour system should include two blowers (one duty, one stand by), each with an inlet filter and silencer, a discharge silencer, automatic start up bypass system, and gages, meters, etc. A header pipe from these blowers will run down the length of the filter gallery with pipe laterals to each filter. Motorized valves on each lateral will allow the filters to be air scoured in conjunction with the water backwash by the automated wash cycle. As the Japanese engineers design will include an air scour system to be compatible with these recommendations (see Section 7.1), CDM recommends their design include a common blower system. Their design utilizes the existing water backwash system it makes sense therefore, for them to include the air scour blower system and tie these into the proposed new header pipe and laterals in the existing filter gallery. The air scour system can be installed at any time. It will not be necessary to close the plant down. Individual filters only, need be shut down for short periods.

With the improvements made to the flocculation and sedimentation basins and filters, it will not be necessary or advisable to backwash every 24 hours. The run time criteria should be set at 48 to 60 hours (no more), the maximum available clogging head should be utilized, and the terminal turbidity should be set lower. Again, this will save on the amount of water used while still achieving the operating water quality goals. Considering electrical costs represent approximately 92 percent of the unit cost water production, the less water used for backwashing the greater the savings. The individual terminal turbidity should be set at 0.1

NTU. The abandoning of the sedimentation basin troughs will benefit the performance of the filters. When taking a filter off-line for backwashing, the change in water level over the filters will be small and slow due to the dampening out effect of the direct connection of the water in the filters and sedimentation basins. This will reduce the rate of flow change of the operating filters, thus improving the water quality. With the proposed disinfection/oxidation modifications, and the high turbidity goal of 0.1 NTU, the inactivation and removal of nematodes can be assured, if the plant is operated and maintained according to appropriate standards.

It is also recommended that the filters be inspected on an annual basis. This should include coring the media and the examination and testing of the media grains over the full depth to check media loss through abrasion, effectiveness of the backwash, evidence of mud ball formation, and evidence of nematodes. When the backwash system is working correctly, there should not be any need for acid or alkaline cleaning of the bed. Regular observation of clean bed head loss following backwashing should be noted. A gradual increase in this value will be an early sign of problems. Surface cracking of the media is another sign the media is not being cleaned effectively. Cracks can lead to short circuiting through the filter.

6.10 Taste and Odor Control

As discussed earlier in this report, tastes and odors are difficult water quality characteristics to effectively identify, monitor, quantify, and control. The plant now has the capacity to control taste and odor events by the use of the oxidant potassium permanganate, the oxidant chlorine, and PAC. The existing PAC feeders each have the capacity to feed approximately 10 mg/L at the maximum 123,000 m³/d plant capacity. Dr. Christoph Czekalla conducted odor tests on the water in mid August and determined a PAC dose of 60 mg/L was needed to reduce the threshold odor number (TON) to 1, i.e., no odor. Dr. Czekalla recommended that provision be made to feed PAC at the rate of 70 mg/L. Currently, the Zai WTP is dosing PAC at about 20 mg/L, using both feeders.

To modify the existing feeders to feed 60 mg/L each of PAC will, according to the manufacturer of the existing units, cost almost as much as replacing the existing with new feeders. Therefore, complete system replacement is recommended.

In the draft report of 30 September 1998, CDM recommended relocating the PAC application point to the chemical injection vault on the raw water pipeline ahead of the regulating reservoir. Test No. 4 of Appendix C, conducted by CDM, compared adding PAC to the raw water ahead of the regulating reservoir to the current practice of adding PAC to the water along with the coagulant chemical at the rapid mixer. This test verified CDM's belief that adding the PAC ahead of the reservoir would allow more time for organic molecules and particles to be adsorbed to the PAC and reduce the PAC dose required to meet the same TON taste and odor reduction objective. The current method is much less effective because the PAC particles become nuclei for coagulant floc formation, thereby depriving surface area for molecule adsorption. The test showed that only 3 mg/L was needed to meet the same TON level to simulating the addition of PAC ahead of the reservoir compared to the 20 mg/L being used at the plant at the time. Although it was not established that 20 mg/L of PAC was necessary nor was it possible to simulate the same taste and odor conditions of July-August 1998, it does demonstrate the effectiveness of this recommendation.

The recommendations, in Section 6.3, "Nematode Inactivation and Disinfection", to relocate the potassium permanganate application point to down at the IPS and to add chlorine dioxide at that location also, will help in controlling tastes and odors. Both chemicals are strong oxidants (AWWA, 1997 and Cooper, 1981) that will oxidize taste and odor compounds. The added contact time allowed for these oxidants as they traverse the conveyance pipeline will add to the facility's capacity to control major taste and odor events. As discussed in the bench scale test results (Appendix C), this pre oxidation will improve the effectiveness of the PAC due to a break down of organic molecules that will have access to more PAC adsorption sites.

The recommended capacity of these units are 5 mg/L for both the potassium permanganate and chlorine dioxide. This dose is more than necessary for normal operations. In fact, it may be possible to use the chlorine dioxide alone most of the time. Time and full plant operational and/or bench scale experimentation will soon determine the optimum conditions. The average anticipated PAC requirement is 3 mg/L when used in conjunction with the other two taste and odor controllers.

Until there is a repeat of the major taste and odor event of July-August 1998, it is not possible to prove the effectiveness of the recommendations. It could be tested bench-scale using Geosmin and MIB as the taste and odor producing compounds. CDM has done this often in pilot plant studies using ozone for taste and odor control and as a disinfectant. However, the problem compounds of July-August have not been specifically identified and until they are or there is a repeat of the episode, there is not a lot one can do that will guarantee a 100 percent solution. Bench scale studies using Geosmin and/or MIB would demonstrate something, as these are among, if not the most, potent algae secreted compounds known.

In the mean time, CDM recommends that the existing PAC feeder system be replaced with two new units each of 35 mg/L capacity at 123,000 m³/d, i.e., 4.3 kg/d. This means that the "standby" unit may need to operate on occasion. This is a reasonable risk to take for two reasons (1), with all the other provisions recommended to aid in taste and odor control in place it is unlikely that anywhere near this dose would be required, and (2), even if it was needed for the short and infrequent occasions when more than 35 mg/L is required, the other unit can be used. It will be advisable to lay a second PAC slurry line up to the chemical injection vault on the raw water incoming pipeline as pipes carrying PAC slurry sometimes become blocked and require cleaning.

Should raw water quality deteriorate in the future, and the events experienced in July-August occur more frequently, it may be more cost effective to replace the existing media with 800 mm depth, or more, of 1 mm effective size granular activated carbon (GAC) and 100 mm depth of 0.5 mm effective size garnet. This will ensure that there will always be a double carbon barrier provided for taste and odor control. The use of garnet in place of sand will mean that the media will not need to be fluidized after backwashing to re-stratify the dual-media because the heavy garnet will not move during the backwash cycle. This will result in less water being used for backwashing thereby reducing operating costs. GAC is often installed in the United States to act as both a filter and an adsorbent of taste and odor compounds, natural organic compounds, and synthetic carbon compounds. If GAC is installed in the filters at the Zai WTP in the future, it would still be advisable to use a small

amount of PAC to handle the background taste and odor, thereby calling on the GAC to handle the occasional high excursions. This will extend the life of the GAC. The cost of replacing the existing filter media with GAC and garnet is estimated at JD 300,000.

A further way to ensure the control of taste and odor is to add ozone to the treatment train. Ozone is being used more and more in the United States, mostly as the primary disinfectant, in an effort to avoid excessive THM formations with raw waters with high amounts of THM precursors. It is also proven to be very effective in oxidizing the normal algae originating taste and odor compounds dissolved in the water, such as Geosmin and MIB. However, the on-site generation and application of ozone is complex and very costly. As pointed out in Section 6.3, until THMs limits are regulated lower than the current Jordanian standard, ozone should not be considered. Monitoring of THMs should be continued. Other disinfectant by-products of chlorine dioxide and chlorine not currently regulated in Jordan should be regularly analyzed for. If and when the standard for THMs is lowered in Jordan, the relative cost of alternative disinfectants that avoid the formation of THMs, and the cost of taste and odor control, can all be evaluated at that time to determine the most appropriate and cost effective combination of control methods for taste and odor and disinfectant by-products.

CDM believes the recommended modifications to be made to the water conveyance system and the Zar WTP, together with the recommended relocation of the PAC and potassium permanganate application points, and the addition of chlorine dioxide, provide the means to ensure complete protection against current and immediate future taste and odor events.

7 0 Review of Japanese Funded Design and German Funded Report

7 1 Japanese Design

CDM reviewed the detailed drawings of the expansion and modifications of the Zai WTP prepared by Tokyo Engineering Consultants Co, Ltd, for the Japan International Cooperative Agency Based upon this review, comments and recommendations on the proposed design concept follow The recommendations made here follow the recommendations for the existing plant made in the preceding sections

- 1 That proposed changes to the raw water regulating reservoir should be modified to comply with the recommended reservoir baffling system as outlined in Section 6 4
- 2 That the flash mixing concept be changed from the mechanical two stage concept to a two stage hydraulic flash mixing concept as proposed in Section 6 5 of this report
- 3 That perforated inlet walls be included in the flocculation basins as proposed in Section 6 7
- 4 That launders and weirs be omitted in the sedimentation basins, and perforated outlet walls be included in the basins, as detailed in Section 6 8
- 5 That the filters include provision for concurrent air scour and water backwash using appropriate underdrains The design should include the air scour blowers and control system and allow for tying into the proposed air header for the existing filters This blower system can be used for both the existing and expansion filters as is proposed for the water backwash system
- 6 That the filter boxes be designed to allow for 1,000 mm of GAC over 100 mm of garnet in the future This allowance will necessitate locating the waste backwash water troughs high enough to avoid GAC media loss
- 7 That the existing and new filter turbidimeters all be fitted with transmitters and included in the filter control system as one of the three criteria for termination of filters, i e , run time, head loss, and turbidity
- 8 That the filters be fitted with provision to add a polyelectrolyte filter aid, to add a polyelectrolyte into the backwash water for filter maturing, incorporate slow start filter flow throughput linearly over 0 60 minutes (adjustable) after backwashing, and allow for filters to rest (in the backwash sequence) for 30 60 minutes (adjustable) after backwashing and before bringing back on-line
- 9 That the existing and new filters all be incorporated into the same programmable computer monitoring and automatic control system

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- 10 That the Japanese design include the use of PAC up to 70 mg/L as stated in Section 6.10. The Japanese design for the plant expansion allows for utilizing one of the existing PAC feeders. Additional feeders will be necessary. Alternatively, two new feeders to feed 35 mg/L each at 236,000m³/d could be furnished. Space wise, this may be the more economic solution. CDM further recommends that the Japanese expanded PAC design system include bag loading conveyors, bag splitters, bag compactors, and dust extractors.
 - 11 The Japanese design proposes to add chlorine to the filtered water only because of the possibility of exceeding the THM standard. However, it is more important at this time to carry chlorinated water on to the filters to aid in the inactivation of nematodes. The need to reduce THM levels should be addressed in the future if and when THM levels in the distribution system are exceeded or the maximum allowable average THM levels are lowered.
 - 12 The Japanese design does not allow for the use of an anionic polymer as a flocculant aid. CDM disagrees and recommends the continued use of a polymer to aid in floc formation. This requirement should be included in the proposed plant expansion.
 - 13 The new wash water recovery pumps in the wash water tank should have variable frequency drive controls to allow a variable but daily constant flow rate back to the head of the plant, based upon plant flow recovery volumes. The automatic plant control system should allow for this. New or larger pumps may not be necessary if a filter air scour system is installed.
 - 14 The design includes additional backwash pumps. CDM does not believe these are necessary. These and the force main can be omitted.

7.2 German Report

CDM reviewed the report prepared by Dr. Christoph Czekalla for CONSULAQUA Hamburg, Consulting Engineers Ltd for the Ministry of Planning of Jordan through the Jordanian/German Technical Cooperation GTZ Amman. CDM's comments on the recommendations of this report are as follows:

- 1 CDM agrees that monitoring of the raw water in the KAC is advisable. A more detailed discussion can be found in Section 9.0.
- 2 Although outside the scope of CDM's assignment, we would agree with the recommendation of water resources management advocated in the German Report.
- 3 CDM does not agree with the concept of using ferric chloride to reduce the nutrient phosphorous in the canal because of other side effects, as discussed in more detail in Section 5.0.

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- 4 CDM supports the investigation of the elements that contribute to algae growth
 - 5 As stated earlier in this report, CDM has recommended an alternative approach to algal control in the pumped conveyance system to the Zai WTP using potassium permanganate, as opposed to the use of copper sulfate as recommended in the German report
 - 6 CDM agrees that the PAC feeding system should be increased in capacity CDM does not see the need to increase the alum dosing rate In fact, CDM has recommended using ferric sulfate as the primary coagulant chemical This will eliminate the need to add an acid feed system as advocated by the German report The addition of an acid will necessitate the addition of a base chemical to the finished water, as well
 - 7 CDM agrees with the making of the anionic polymer dosing points to aid in floc formation permanent CDM has gone further and recommended providing alternative application points at both the second and third flocculator stages for added flexibility
 - 8 CDM agrees that standby feeders, metering equipment, and spare parts should be available With the Japanese adding to and modifying the chemical systems to cover the existing and expanded plant, they should allow for adequate standby facilities and spares
 - 9 CDM agrees with the change over from the existing filter surface wash concept to an air scour facility
 - 10 CDM does not agree with the concept of adding filter-to-waste in an existing plant There are other methods that can be used to meet the object of eliminating the initial turbidity spike CDM has recommended these alternatives in Section 6.9 of this report
 - 11 CDM does not see any water quality reason to accelerate the draining of the sedimentation basins
 - 12 CDM does not agree that an additional two backwash and sludge decant recovery tanks are needed However, the recovered water should be returned to the head of the plant at a steady and consistent rate over 24 hours This means the recycle pump motor controls should be changed to allow these pumps to operate at variable speeds and, therefore, flow rates If the Japanese expansion requires bigger pumps, they should include variable speed pump motors and automatic controls in their design
 - 13 As discussed in this CDM report, the use of ozone is not warranted or economically justified at this time
 - 15 CDM agrees that an alternative disinfectant be investigated, although for

slightly different reasons than those given by Dr Czekalla CDM has recommended the use of chlorine dioxide ✓

- 16 CDM agrees with the recommendation of using GAC in the filters, but only in the future if and when its use is proven to be required and is economical
- 17 CDM agrees with the recommendation of changing from alum to a ferric salt as a coagulant CDM has evaluated the effectiveness and cost merits of using ferric chloride and ferric sulfate as opposed to alum and has recommended the use of ferric sulfate

8.0 Prioritization

The CDM recommended modifications contained in this report have been prioritized below, the first having the highest priority and the last the lowest. CDM highly recommends that all of the recommendations be implemented together. However, if omissions were to be made, then the recommendations CDM would propose for omission would be numbers 14 and 15, since the pump station balancing tanks could be kept free of algae by operators regularly flushing them out. However, a lot of water would be wasted in the process.

The CDM recommended modifications and additions contained in this report are designed to meet the control of tastes and odors and nematodes. Other benefits such as THM formation potential reduction are coincidental and not primary considerations. If for some reason the staggering of their implementation were desirable, then the following arrangement would be CDM's recommended order:

- 1 Relocate the PAC application point to the chemical injection vault on the raw water pipeline ahead of the regulating reservoir. Relocate the chlorine application point to the settled water channel.
- 2 Convert from alum to ferric sulfate as the primary coagulant.
- 3 Replace the existing PAC feeders and slurry feed pumps with new feeders and pumps to allow feeding PAC at 35 mg/L capacity each at the expanded plant flow of 246,000 m³/d.
- 4 Add a potassium permanganate application point at the Intake Pump Station.
- 5 Baffle the regulating reservoir at the Zai WTP.
- 6 Add chlorine dioxide dosing facilities at the Intake Pump Station.
- 7 Change over the existing mechanical flash mixing system to a hydraulic flash mixing system.
- 8 Add the perforated inlet walls to the flocculation basins, change the motor speeds for all flocculators to their low speed, and apply polymer at the impellers.
- 9 Add outlet perforated walls to the sedimentation basins.
- 10 Modify the filters to eliminate the turbidity spike after backwashing.
- 11 Add a filter aid polymer system.
- 12 Provide an air scour for the filters.
- 13 Convert fixed-speed recovery pumps to variable speed.

14 Modify the piping at the storage tanks at Pump Stations 2, 3, and 4

15 Add baffles in the storage tanks at Pump Stations 1, 2, 3, and 4

Many of these recommendations offer more than one benefit in water treatment, making their grouping into priority "packages" difficult

In CDM's judgment, taste and odor in the water is of greater concern than nematodes. The recommendations which deal most directly with the taste and odor issue include recommendations 1 and 3 - 6

The recommendations dealing most directly with nematode issues are 2 and 8 - 13, although 6 will provide great benefit, as well. Recommendation 2, involving the conversion of alum to ferric sulfate coagulant, is listed second in priority, however, since it can be implemented immediately, at essentially no cost, and with immediate benefits for improved settling characteristics in the sed basins

Recommendation 7, involving improved coagulant and polymer mixing methods, is strictly a cost-saving measure which is listed as a medium priority because of its ability to quickly pay for itself, while requiring a day or less of plant downtime to implement

Recommendations 14 and 15 also deal most directly with the taste and odor issue but, as explained earlier in this section, are lower in priority since their impact is less than the other related recommendations. Also, close supervision and regular, manual flushing by an operator could provide the same result in preventing water stagnation

9.0 Water Quality Monitoring

CDM has reviewed the Norwegian (CESAR) Proposal on an Early Warning Water Quality Monitoring System for the Water Supply to Amman. This system is very comprehensive and costly, calling for six monitoring stations located along the KAC, at the Intake Pump Station, and at the inlet to the Zai WTP. Each station would monitor seven parameters: pH, O₂, turbidity, conductivity, UV absorption, PO₄-A, and ammonia. Each station would be fitted with automatic samplers and results transmission capability to the control room of the Zai WTP.

An early warning system to advise the operators at the Zai WTP would be beneficial. However, if too much raw water data or samples are fed to the plant to be analyzed, it could result in the plant chemists and biologists being overwhelmed. Taste and odor events can be intermittent, and analyzing all this data without an event occurring can result in analysts becoming lethargic. When a taste and odor event does occur, it could be through the plant before the compounds causing the event are detected. Further, the cost of the sampling program and analytical work recommended by the Norwegians will be very high.

The CDM (Medler/Horsefield) 13 August 1998 Greater Amman Water Problems Report recommended continuous monitoring of pH, regular counting of taste and odor causing algae, plotting the counts against time to identify rapid increase in numbers, installation of automatic chlorophyll-*a* analyzers at a location(s) giving sufficient time for plant operators to be prepared. Often, simplicity is the best answer, and CDM, therefore, recommends locating a single automatic monitoring station with telemetering provisions approximately 30 km upstream from the Deir Alla intake. This station should analyze for pH and chlorophyll *a*. Manual samples should be collected every second day and examined for taste and odor producing algae, nutrients and TON tests should also be performed. These samples should be collected at the top of the KAC, and at the 15 km and 30 km downstream milestones.

During recent discussions at WAJ in preparation for finalizing this report, the suggestion was made to consider operating the clearwells as two separate chambers—one for flow-through to Pump Station No. 5 and the distribution system, and the other for temporary retention in order to first run quality tests before releasing the water to the distribution system. Each chamber would alternate in retaining or supplying water.

CDM believes this mode of operation would be impractical, given the number of tests which would be required, both day and night. Also, these tests would need to be performed within an extremely short timeframe, since at the expanded plant capacity, a retention time of only about one hour will be available. CDM is not familiar with any other plants which operate their clearwells in this manner.

10 0 Costs

10 1 Operating and Capital Costs for Alternative Chemical Systems

CDM has suggested in the preceding Sections a number of changes that would affect the operating costs, primarily so far as alternative chemicals are concerned. If other operational factors impact the comparative costs than these are also included as noted. Polyelectrolyte chemicals are common to all alternatives and therefore, are not included in this cost comparison. Three basic alternative combinations of chemicals fall out. These are

Alternative A	Potassium Permanganate Chlorine Dioxide Powdered activated carbon Ferric sulfate Chlorine
Alternative B	Potassium permanganate Chlorine dioxide Powdered activated carbon Sulfuric acid Aluminum sulfate (Alum) Caustic soda Chlorine
Alternative C	Potassium permanganate Ozone Ferric sulfate Chlorine

Table 10 1 shows the various chemicals under consideration. This table gives the anticipated doses of each, their unit cost per tonne, the annual cost of each, and the total annual cost for each chemical and combination of each of the three Alternatives. The operating costs are in line with CDM's recommendations earlier in this report for reasons other than cost. Alternative B is the least expensive chemical cost-wise. Although, considering the level of estimating for a report, the cost difference between Alternatives A and B is small. However, Alternative A uses a lesser number of chemicals and for that reason Alternative A is preferred. Operationally, Alternative B uses some undesirable chemicals, namely sulfuric acid and caustic soda. The control of these chemicals would be difficult with little, if any, benefit over Alternative A.

TABLE 10-1
ANNUAL CHEMICAL COSTS OF ALTERNATIVE COMBINATIONS

CHEMICAL	DOSE (mg/L)		UNIT COST (JD/TONNE)	COST PER YEAR(4) (JD x 1,000)	
	EXISTING	PROPOSED		EXISTING	PROPOSED
KMnO ₄	1.3	1.5	2,600	152	175
CHLORINE DIOXIDE	0	1.5(1)	NaClO ₂ 4,125 Cl ₂ 400	0	211
PAC	20	3	1,000	898	135
ALUM	45	40(2)	200	404	360(3)
FERRIC SULFATE	0	20(2)	965	0	866
SULFURIC ACID	0	3.5	548	0	86(3)
CHLORINE	3	1.5	400	54	27
CAUSTIC SODA	0	5	2,040	0	458(3)
OZONE	0	2	16,000	0	1,437
TOTALS	EXISTING			1,508	
	ALTERNATIVE A, using ferric sulfate			1,414	
	ALTERNATIVE B, using alum with pH adjustment			1,241	
	ALTERNATIVE C, using ozone in lieu of chlorine dioxide			2,505	

(1) Made up of 1.1 NaClO₂ plus 0.4 Cl₂ (2.68:1.00 ratio assuming 95% efficiency)

(2) Reflects reduction in dose needed due to mixer improvements (see Section 6.5)

(3) Alternative to ferric sulfate

(4) mg/L x 123 x 365 x Cost/tonne x 1/1,000

Table 10-2 sets out the capital cost of equipment for chemicals that come into the comparison of chemical alternatives, namely chlorine dioxide, sulfuric acid, caustic soda, ferric sulfate, and ozone. KMnO_4 and chlorine are not included as these are common to all Alternatives. These capital costs are presented as an annual sinking fund cost, i.e., the cost to borrow money and pay it back the loan based upon 20 years and 6 percent.

TABLE 10-2
CAPITAL AND SINKING FUND COSTS

CHEMICAL EQUIPMENT	CAPITAL COST (JD x 1,000)	ANNUAL COST(1) (JD x 1,000)
CHLORINE DIOXIDE	650	18
PAC	200	5
SULFURIC ACID	78	2
CAUSTIC SODA	203	6
FERRIC CHLORIDE(2)	0	0
OZONE	3,200	87

(1) Sinking Fund, based upon 20 years and interest at 6%, i.e., factor of 0.0272

(2) Existing alum feeders used for ferric sulfate

Table 10-3, on the next page, combines the annual chemical costs from Table 10-1 with the sinking fund costs from Table 10-2.

TABLE 10-3
CHEMICAL ANNUAL OPERATING AND SINKING FUND COSTS

CHEMICAL COST (JD x1,000/Year)	ANNUAL COST (JD x1,000)	TOTAL ANNUAL COST (JD x1,000)
211	18	229
135	5	140
86	2	88
360	0	360
458	6	464
866	0	866
1,437	87	1,524
ALTERNATIVE A		1,235
ALTERNATIVE B		1,281
ALTERNATIVE C		2,390

10.2 Capital Costs for Individual Items

CDM has estimated the cost of the individual items recommended for modification in this report. These are listed below in order of the priorities recommended.

- 1 Relocate the PAC application point to the injection vault at the inlet to the regulating reservoir. Relocate the chlorine application point to the settled water channel. JD 0
- 2 Convert from alum to ferric sulfate. JD 0

3	Replace the existing PAC feeders and replace the slurry pumps with larger pumps as recommended in Section 6 10	JD 200,000
4	Add potassium permanganate feeders at the Intake Pump Station as described in Section 6 2	JD 85,000
5	Baffle the Raw Water Regulating Reservoir as recommended in Section 6 4 and as detailed in Figures 6 4-1, 6 4-2, and 6 4-3	JD 40,000
6	Add chlorine dioxide facilities at the Intake Pump Station	JD 650,000
7	Modify the Flash Mixing as recommended in Section 6 5 and detailed in Figures 6 5-6 and 6 5-7	JD 10,000
8	Modify the flocculation basins, including the inlet baffle walls, and install flocculation polymer aids in the second and third stages of flocculation as recommended in Section 6 7 and shown in Figures 6 7 1 and 6 7-2	JD 5000
9	Modify the sedimentation basins, which includes adding a perforated outlet wall and adding sluice gates, as recommended in Section 6 8 and detailed in Figure 6 8 2	JD 15,000
10	Modify filter controls to eliminate the turbidity spike, as recommended in Section 6 9	JD 88 000
11	Add a filter aid polymer system to improve filtration performance, as recommended in Section 6 9	JD 90,000
12	Add an air scour system to filters as recommended in Section 6 9 The air scour blowers and controls should be included in the Japanese part of their expansion design	JD 450,000
13	Convert fixed-speed motors on wash recovery pumps to variable speed, and modify control system to recycle recovered water at a constant rate over 24 hours, as recommended in Section 7 2, Item 12 (this change should be included in the Japanese phase of the project)	JD 25,000
14	Modify and add piping and valves for the storage	JD 220,000

tanks at Pump Stations 1, 2, 3, and 4 in accordance with Section 6.2 and as shown in Figures 6.2-1, 6.2-2, 6.2-3, and 6.2-4

- 15 Baffle the storage tanks at Pump Stations 1, 2, 3, and 4 in accordance with the recommendations in Section 6.2 and as shown in Figures 6.2-1, 6.2-2, 6.2-3, 6.2-4, and 6.2-5 JD 35,000

11 0 Bench-Scale Test Results Summary

CDM, in the Draft Report of September 30, 1998, recommended a series of bench-scale tests be conducted. These included Test No. 1, to determine the potential trihalomethane (THM) formation if the chlorine was added to the raw water at the Intake Pump Station (IPS), Test No. 2, to better identify ways to kill or inactivate nematodes, Test No. 3, to compare alternative coagulation chemicals, and Test No. 4, to evaluate the effectiveness of relocating the application points of some chemicals. A summary of these test procedures, results, and interpretations is included in this Section. As and where appropriate, previous recommendations in this report are based upon these test results.

Appendix C contains the test protocols, tests, and interpretations in a detailed report. An introduction to each of the four tests is followed by details of test procedures, the results, and a discussion section. Conclusions and recommendations at the end of each test section put the test in context in terms of associated recommendations for plant upgrading and/or process changes. Other information and suggestions are provided as considered appropriate, including supporting documentation from plant design and water quality literature.

A Laboratory Implementation Group formed in Jordan helped hone and plan the work. The group discussed a number of issues, including needs for watershed protection and for further protection of water quality within the distribution system. It was noted that the peak taste and odor episode had ended, making it difficult in some cases to extrapolate laboratory results to worst-case conditions.

Test No. 1 investigated raw water oxidation at the IPS with chlorine or potassium permanganate (KMnO_4). Raw water samples were exposed to an oxidant as if it were added at the IPS, and then treated according to plant simulation protocols. These protocols followed two flow rate scenarios: high flow rate (after the planned doubling of the Zai Water Treatment Plant) and low flow rate (half the current WTP and raw water main capacity). Temporal changes in THM formation were then monitored as if the product water was traversing the distribution system under summer (worst-case) conditions.

Test No. 1 results indicated that preoxidation at the IPS with either chlorine or KMnO_4 followed by simulated Zai WTP treatment, including chlorine addition, can result in THM levels above Jordanian standards. THMs formed during initial prechlorination stages decreased due to THM volatilization and to adsorption of THMs and THM precursors onto PAC during the treatment simulation.

The Jordanian THM standard of 150 parts per billion (ppb) was exceeded for the prechlorination simulating high flow rates. For the low flow rate simulation, prechlorination did not result in THM levels exceeding Jordanian standards over the eight day monitoring period. This unexpected result was likely due to several factors (or combinations of factors): volatilization of THMs initially formed, powdered activated carbon (PAC) adsorption of these compounds, oxidation of THM precursors by chlorine, formation of other total organic halogen (TOX) compounds such as haloacetic acids (of relatively recent health and regulatory concern), and/or experimental error.

KMnO_4 preoxidation resulted in higher THM concentrations than for prechlorination. This

result is similar to results sometimes obtained with ozone (AWWA, 1990). However, as suggested by the Test No. 4 results, KMnO_4 addition at the IPS can still be effective for taste and odor control without causing increases in THM levels. Actual better field results from using KMnO_4 to those used in the laboratory tests are possible because of the higher turbulent mixing conditions in the raw water conveyance system. Resulting increases in oxidation may reduce the THM formation potential of the raw water, particularly in conjunction with the recommendation to relocate the PAC feed point ahead of the regulating reservoir. Experimental uncertainty and the inability to perform statistical analyses must also be considered in evaluating the results.

Test No. 2 procedures focused on effects of the following oxidants on nematode motility: KMnO_4 , chlorine, chloramines, and chlorine dioxide. A fifth examination of a mixture of KMnO_4 and chlorine was conducted because this approach is currently used at the Za1 WTP.

Sufficient quantities of nematodes could not be found at the King Abdullah Canal (KAC) or at the WTP, so cultures of the nematode *Cephalobus* were imported. Results for the *Cephalobus* indicate that they will not be inactivated by KMnO_4 or chlorine, or a blend of the two, at feasible concentrations within reasonable times. While chloramines at high concentrations were effective to some extent, only a very strong oxidant such as ozone or chlorine dioxide can provide maximum assurance that nematodes will be inactivated. Chlorine dioxide proved very effective at inactivating the *Cephalobus* nematodes under test conditions. However, concentrations of chlorine dioxide required for inactivating these nematodes may result in the chemical concentrations of the inorganic reaction product chlorite ion exceeding planned U.S. EPA recommended levels, but as yet unregulated in Jordan.

Removal of nematodes and pathogens such as *Giardia lamblia* and *Cryptosporidium* can be maximized by optimizing all treatment steps. Maximizing filter performance is a key factor in removing nematodes. Highly appropriate recommendations are given in this report include improved filter media and air scour. Improving sedimentation basin performance by eliminating the finger weirs and replacing them with baffle walls will aid filter performance, as will adding polyelectrolytes as a filter aid and during the last few minutes of backwashing.

Test No. 3, jar tests, compared alum (used presently at the WTP) with ferric sulfate and ferric chloride. Prior to most of the jar tests, oxidation of raw water at the IPS was simulated using KMnO_4 doses matching those in use at the plant at the time. WTP simulation protocols were then followed.

Jar test results indicate the ferric salts work reasonably well. Under test conditions, ferric chloride worked better than ferric sulfate or alum, but suppressed pH values somewhat more than did the other coagulants. Alum worked better under test conditions than ferric sulfate using the coagulant aides available. Slightly high doses (above optimum) of the ferric chloride solution studied imparted a yellow color to the settled water.

Efforts to use acid for lowering pH values with alum may help both coagulation and with decreasing aluminum solubility. Dissolved aluminum concentrations are often above the Jordanian recommended level of 0.1 ppm, and often approach the Jordanian maximum level, 0.2 ppm. However, some caustic soda (or lime or soda ash) may have to be added later to

prevent corrosion and/or colored water problems in the distribution system. It is likely that ferric sulfate would function better with a different polyelectrolyte, and/or ferric polyelectrolyte combination, than the one currently in use with alum. Current cost data indicate that alum is less expensive than the other two coagulants. However, if pH adjustment(s) is needed for alum, total costs for alum use increases.

Test No. 4, PAC testing, targeted two suggested improvements for taste and odor control at the plant: providing a KMnO_4 feed system at the influent pump station (IPS), and PAC feed at the regulating reservoir influent. Because this testing was performed after the major July-August 1998 taste and odor episode, test conditions cannot indicate precise means for addressing a problem event. Nevertheless, information on the relative effects of new KMnO_4 and PAC feed locations were obtained.

The results indicate that the combination of KMnO_4 oxidation at the IPS followed by PAC addition at the regulating reservoir will require less PAC than used at present for taste and odor control. In fact, it is possible that with a long preoxidation stage, PAC may not be required for taste and odor control under present conditions. However, it is difficult to extrapolate these results to the compounds responsible for the summer taste and odor episode, which may have different oxidation and adsorption properties.

In the simulations of KMnO_4 addition at the IPS, adding PAC well before the coagulation stage resulted in less THM formation than when PAC is added just before coagulation. Thus, it is likely that PAC addition at the regulating reservoir removed THM precursors, regardless of whether KMnO_4 increased THM formation potential as suggested by the Test No. 1 results. However, other TOX compounds should be considered in examining these THM results. While PAC appears to have decreased THM formation, other as yet unregulated TOX by-product compounds, such as haloacetic acids (HAA), may have been produced in unknown quantities.

A test where KMnO_4 and PAC added simultaneously also indicated that adding PAC well before coagulation lowers PAC dosage requirements. However, effects on THM (and TOX) formation were not determined for this experiment.

These observations bolster the recommendation of adding a second KMnO_4 feeder to the IPS, and adding PAC to the raw water at the injection vault on the raw water line feeding the regulating reservoir. This arrangement will provide added operational flexibility to respond to the next taste and odor episode.

APPENDICES

APPENDIX A

REFERENCED REPORTS AND MATERIALS

APPENDIX A Referenced Reports and Materials

- 1 Report, Greater Amman Water Problems July August 1998, Camp Dresser & McKee International Inc , 13 August, 1998
- 2 Study Report for Implementation Review of the Project for Improvement of Water Supply System to Greater Amman Stage II in the Hashemite Kingdom of Jordan, December, 1997, Japan International Cooperation Agency
- 3 Preliminary Report, Water Quality Investigations, Zai Water Treatment Plant, August 18, 1998, Stanley Consultants Inc
- 4 Recommendations for Modifications of the Water Treatment Systems at Zai Water Treatment Plant, August 23, 1998, Dr Christoph Czekalla
- 5 Proposal on an Early Warning Water Quality Monitoring System for the Water Supply to Amman, August 31, 1998, Centre for Environmental Studies and Research Management, Oslo, Norway
- 6 Pipeline from Pump Station No 5 to Dabouq Reservoir, Deir Alla-Zai Amman Water Expansion Project Stage II, Stanley Consultants Inc Drawings
- 7 Intake Pump Station Expansion, Settling Basins, and Pump Station No 5 Expansion, Deir Alla-Zai-Amman Water Expansion Project Stage II, Stanley Consultants Inc Drawings
- 8 Raw Water Sources, Zai Water Treatment Plant, and Associated System, Draft Report on Water Quality and Water Treatment Investigations, CONSULAQUA Hamburg, Consulting Engineers Ltd , August, 1998 for German Technical Cooperation (GTZ)
- 9 Draft Report on Drinking Water Quality in Amman Jordan, Dr Houssain Abouzaid and Dr Mouhammed Ali Khan, of World Health Organization
- 10 Various Zai Water Treatment Department Reports
- 11 Kaeamuru, Susumu, *Intigrated Design of Water Treatment Facilities*, John Wiley and Sons, New York (1991)
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- 13 AWWA, *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*, October, 1990
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- 15 Pontius, F W , J AWWA, 90 (3) (March 1998)
- 16 Cooper, William J , Editor, *Chemistry in Water Reuse*, Volume 1, Chapter 20, Ann Arbor Press Ann Arbor, MI (1981)

APPENDIX B

SCOPE OF WORK

APPENDIX B Scope of Work

“SCOPE OF WORK, Emergency Assistance for Zai Water Treatment Plant Operations

Technical Assistance, and Commodity and Construction Procurement Services

Based upon the current and expected raw water quality of the Zai plant system, the contractor shall re assess the required chemical treatment processes of the plant from the raw water intake structure through the Zai plant treated water discharges. This should include assessment of the chemicals required and dosage rates, dosing equipment capability, and efficiency of operations. Based upon this assessment, including review of available plant operations and raw water quality historic data, and recent CDM and Stanley Consultant reports on plant operations and effectiveness, the contractor shall provide alternative options, recommendations, and cost analyses for permanent modifications to the plant and treatment. Subsequent WAJ and USAID approval and selection of a recommended option to be implemented via an amendment to the IQC contract.

The contractor shall review the proposed German and Japanese funded plans for expansion of the Zai plant to double its capacity, to assure plant operational compatibility and uniformity between the German and Japanese plans and proposed CDM modifications in plant operations and facilities.”

APPENDIX C

BENCH-SCALE TEST RESULTS

APPENDIX C Bench-Scale Test Results

Introduction

This report summarizes a group of laboratory experiments conducted at the Zai Water Treatment Plant (WTP), which serves a large portion of the population of Amman, Jordan. In the summer of 1998, a bloom of taste and odor producing algae resulted in severe customer complaints and management turnover. Nematodes were discovered within the system during the resulting investigations. The work described in this report was initiated to aid with finalizing recommendations made in this CDM Report and analysis of conditions at the Zai WTP (CDM, 1998). These recommendations targeted helping the plant improve its capability to respond to future taste and odor events, and to enhance removal of nematodes by plant unit operations. Four test protocols were suggested.

During preliminary planning, it was recognized that the testing protocols were extremely ambitious in terms of available resources and time, and associated needs for methods development. However, every effort was made to meet the goals and objectives of the original plan. As a component of this approach a Laboratory Implementation Group was set up during initial meetings in Amman. This group consisted of Dr. Narwal Sunna (Water Authority of Jordan [WAJ]), Dr. Murad Jabay Bino (Executive Director, Inter-Islamic Network on Water Resources Development and Management), Dr. Barnes Bierck (CDM), Ms. Mageda Alzoubi (WAJ Zai WTP), and Mr. Haitham Kilani (WAJ Zai WTP). Dr. Bierck was responsible for directing the work and preparing the report. The Laboratory Implementation Group held numerous meetings, helping modify testing protocols to adapt to current conditions, available resources and constraints.

The Laboratory Implementation Group discussed a number of issues. Ferric chloride was being added many kilometers upstream from the intake in the King Abdullah Canal (KAC). To eliminate effects of this chemical addition, Dr. Murad Jabay Bino arranged to have the ferric chloride feed temporarily halted. The importance of watershed study and protection was noted, as were effects of distribution system factors on the quality of water reaching consumers. Other issues and decisions made by the Laboratory Implementation Group are noted along with test descriptions below.

At the time of this testing, the raw water no longer exhibited the problem taste and odor characteristics of July and August 1998. Emergency work, including disinfecting the filters and some process changes, are likely to have helped reduce nematode counts. Characteristic taste and odor algae were being identified at times, but in insufficient quantities to create problems. This factor bears directly on follow up taste and odor testing, making it difficult to compare PAC dosages effective at present to those found necessary during the episode.

Each test is discussed in detail below. An introduction to each test is followed by details of test procedures, and a results and discussion section. Conclusions and recommendations at the end of each test section help put the test in context in terms of associated recommendations for plant upgrading and/or process changes. Other information and suggestions are provided as considered appropriate, including supporting documentation from plant design and water quality literature.

Acknowledgments

The help provided by many people is very much appreciated. The excellent original formulation of the laboratory studies, study results evaluation, and recommendations of the authors of the September 30, 1998 Draft Report guided the entire project. Their help and advice helped further hone the testing program.

Mageda Alzoubi, Saleh Malkawi, Sali Zenati, Jamal Ibrahim, and Sahar Kharbat were among the many at the Zai WTP who provided much practical help and advice. Dr. Murad Jabay Bino was a constant source of ideas and inspiration. Dr. Narwal Sunna helped also to crystallize a feasible approach addressing the goals of the project. Dr. Muna Hindiye and Mr. Emad Eddadu of the Royal Scientific Society, along with others at the Zai WTP, helped tremendously with the nematode study.

Others at CDM were extremely helpful. The entire staff at the CDM Amman office provided a nice and productive working environment and tremendous assistance and guidance. Others in CDM's US offices, including the Environmental Health Project, helped as well and this help is much appreciated.

Test No. 1 - THM Formation

Introduction

Test No. 1 was developed to investigate raw water chlorination at the influent pumping station (IPS). Raw water samples were exposed to chlorine as if it were added at the IPS and then were treated using chemicals and treatment procedures in place at the plant at the time. Following this full complement of testing, samples were taken for subsequent trihalomethanes (THMs) analyses. A test simulating use of potassium permanganate instead of chlorine at the IPS was added to the protocol. All testing procedures are described in detail below.

The Laboratory Implementation Group modified the THM formation procedure targeting specific treatment options and associated issues. The committee considered the odds to be very high that the prechlorination approach would lead to THM levels exceeding Jordanian standards.

The committee elected to test two contact times to simulate addition of chlorine at the IPS. The contact time used is the time required for pumping the raw water to the regulating reservoir at the plant (at which point potassium permanganate is currently added). The times chosen were one half the existing raw pumping and plant capacity (i.e., one half of 123,000 cubic meters per day [m³/d]), and twice the existing capacity, i.e., 246,000 m³/d. The smaller value is the lowest water production rate used by the plant, while the higher value will be attained after the planned doubling of the plant's capacity (which will not include enlarging the raw water pipeline).

Note that raw pumping methods vary--the operators can make use of storage in basins at the

pump stations, such that sometimes the IPS is operated at less than half capacity even when the plant flow is half its maximum capacity. Incorporating such operations complexities into the testing was considered unnecessary for the testing program.

It was decided to "incubate" samples of raw water with different chlorine dosages for the two calculated contact times, and to select the samples resulting in total chlorine residuals closest to 0.2 mg/L for the plant simulations.

A third THM test was also added to the protocol. This test procedure simulated addition of KMnO_4 at the raw pump station for the raw water conveyance time after the plant expansion. The sample was then treated following the plant simulation protocol for Test No. 1.

It was agreed that it would be optimal to use incubation temperatures equivalent to the maximum water temperatures found. Warm temperatures were considered the best approach because such temperatures represent "worst-case" conditions during which THM formation would be greatest.

Following the incubation period, the samples were to be treated as at the plant, using the jar test apparatus. Chlorination and filtration simulations were included, and finally a group of samples were taken for THM analysis. To simulate worst case conditions for THM formation during summer, final samples for THM analysis were held in the dark at 28 degrees C. This temperature condition is the one available at the WAJ laboratories, where THM analyses are performed on a regular basis.

Regarding THM formation kinetics, it was originally suggested that THM analyses be carried out to an endpoint equivalent to the maximum travel time in the distribution system. However, the committee considered it unnecessary to estimate and use as an endpoint the time of conveyance to the furthest customer. Estimating this time is complicated by a number of factors including point-of-use water storage and intermittent water provision schedules. Instead, measuring the maximum THM concentration formed over time was considered to be an effective approach for the present testing program. It was decided that daily THM testing for one week would suffice. Testing laboratory resource limitations and the committee's opinion that the prechlorination procedure would result in THM levels exceeding Jordanian standards were additional factors leading to the decision to limit kinetics testing to a one-week period.

Testing Procedure

Nominal residence times in each treatment process for the three components of Test No. 1 (labeled 1A, 1B, and 1C) are shown in Table C-1. These times were used for simulating plant operating conditions as described below. Note that the residence time in the regulating reservoir was determined assuming that it will be baffled to promote a near plug flow regime.

Table C 1
Plant Residence Times

System Component	Residence Time with System at Double Capacity Tests 1A and 1B	Residence Time with System at Half Capacity Test 1C
Raw Water Pipeline	1.6 hr	6.5 hr
Regulating Reservoir	0.5 hr	4.0 hr
Rapid Mix	11 sec	22 sec
Flocculation	33 min	66 min
Sedimentation Basin	3 hr	6 hr

Tests 1A and 1B were run concurrently. Test 1A was a test simulating addition of chlorine at the IPS, while Test 1B simulated addition of KMnO_4 at the IPS.

Test 1A was begun by setting up a series of 12 one liter glass flasks containing raw water from the KAC intake. Measured volumes of a stock solution of 1,100 ppm chlorine were added to paired raw water samples, resulting in 5 pairs of one-liter samples with chlorine dosages of 0.5, 1.0, 1.5, 2.0 and 2.5 ppm. The stock chlorine solution was made from a solution of Hypex, which is a 6.5% solution of sodium hypochlorite similar to Chlorox. Chlorine residual concentrations were measured using a Hach Model CN-66 DPD test kit. This approach was taken to minimize sample volumes used for measuring chlorine residuals. After 1.6 hours at ambient temperature, it was determined that the sample pair dosed at 1.5 mg/L chlorine resulted in a total chlorine residual concentration of 0.2 mg/L. A 40 ml portion of this sample pair was preserved with thiosulfate and held for later THM analysis.

Za1 WTP stock solutions for plant jar testing were used for subsequent process simulations, except for chlorine solution which was made up as outlined above.

Next, 2.3 mg/L of KMnO_4 was added to each one liter flask, and the two flasks were allowed to sit for 30 minutes to simulate conditions in the regulating reservoir. The concentration of KMnO_4 was the same as that being added to the regulating reservoir at the time of the test. The samples were exposed to sunlight for a few minutes toward the end of the 30 minute period. Exposure to light was considered a conservative approach, simulating day time conditions which promote KMnO_4 dissipation in the regulating reservoir through sunlight exposure.

Jar testing was then performed using the plant jar test apparatus. All chemical additions produced the same concentrations as used in the plant itself at the time of testing, i.e., alum at 45 ppm, cationic polyelectrolyte at 1.5 ppm, and powdered activated carbon at 20 ppm. These chemicals were added while stirring the water samples at 130 rpm. Rapid mixing continued at 130 rpm for 1 min, followed by gentle stirring at 30 rpm for 22 minutes to stimulate floc formation, at which point 0.01 ppm of anionic polyelectrolyte was added.

Stirring at 30 rpm continued for another 11 min, then stirring was stopped for a 3 hour period to allow the floc to settle

The samples still were pink from KMnO_4 addition at the end of the flocculation step. In addition, the flocs appeared similar to those produced during a plant jar test performed a few hours before Test 1A. These flocs appeared normal, yet some PAC laden particles floated to the water surface, remaining there throughout the testing. The samples were no longer pink following the 3 hour settling period.

Following the settling period, sedimentation, the turbidity of the water was 1.6 NTU. The clear middle portion of water was removed and chlorine was added until the total chlorine residual measured 1.2 mg/L (matching the target value then at the plant, prior to filtration). The sample was then filtered through 9.0 cm Whatman GF/C filter paper in a Buchner funnel and the residual chlorine was increased to 1.65 ppm, again as practiced at the plant. A 40 ml portion was taken and preserved with a few crystals of thiosulfate for THM analysis. A series of unpreserved 40 ml portions were taken and held for THM analyses over the following week.

Test 1B was run together with Test 1A, following essentially the same procedure with two, one liter water samples. Instead of chlorine, however, incubation for Test 1B was performed using 2.3 mg/L KMnO_4 for 2.1 hr, simulating the future residence time in the raw water pipeline (following the plant expansion) plus the residence time in the regulating reservoir (after baffling). Test procedures from that point were the same as for Test 1A. Following the settling phase, the settled water turbidity was 1.03 NTU. The prefiltration chlorination step resulted in a total chlorine residual of 1.2 mg/L, while chlorination following filtration resulted in a total chlorine residual of 1.60 ppm. A 40 ml portion was then taken and preserved with a few crystals of thiosulfate for THM analysis. A series of unpreserved 40 ml portions were taken and held for THM analyses over the following week.

Test 1C was run in a manner similar to Tests 1A and 1B. A series of pairs of one liter samples of raw water were dosed at 2, 4, 6, 8, 10, and 12 ppm chlorine with the chlorine stock solution. Following a 6.5 hour incubation time at ambient temperature, the sample pair dosed at 2 ppm had a chlorine residual of 0.1 ppm chlorine, and was closest to the 0.2 ppm criterion. Thus, this sample was used for subsequent testing following the procedure as for Test 1A, but following the timing sequence shown in Table C.1. Prior to the treatment procedure a 40 ml portion was preserved with a few crystals of sodium thiosulfate for THM analysis. Following settling, the turbidity of the settled water was 0.51 NTU. The prefiltration chlorine residual adjustment resulted in a total chlorine residual of 1.15 ppm, while the post-filtration chlorination step resulted in a chlorine residual of 1.55 ppm. A 40 ml portion was taken and preserved with a few crystals of thiosulfate for THM analysis. A series of unpreserved 40 ml portions were taken and held for THM analyses over the following week.

Results and Discussion

Results are summarized in Table C-2. THM levels following incubation, simulating chlorination at the IPS, are in line with expectations. The THM concentration of 113 ppb for Test 1C was greater than the Test 1A high flow result of 86 ppb due to the longer

reaction time afforded by Test 1C and the higher initial chlorine dose

Following treatment simulations, the THM levels were reduced due to PAC adsorption. However, THM levels were slightly greater for Test 1A than for Test 1C. This result was due to a number of factors. The jar test treatments, chlorination, and filtration steps were, of necessity, performed out in the open, permitting THM losses to the atmosphere. Such THM losses are likely to have been greater during Test 1C treatment simulations (which took far longer) than for Test 1A. The residual chlorine level following treatment was slightly greater (by 0.1 ppm) for Test 1A than for Test 1C, possibly creating more THMs during chlorination treatment in Test 1A than for Test 1C. In addition, PAC adsorption of THMs may have been more efficient during the Test 1C jar testing than during the Test 1A procedures. Given the limited time available for testing, it was not possible to generate sufficient data to permit statistical analyses to shed further light on these phenomena.

Results for the Test 1B sample following the treatment simulation are reasonable. The chlorine contact time was short at that stage, such that the THM concentration was 21.3 ppb soon after treatment. Note however, that for subsequent days this sample, which had been pre-oxidized with KMnO_4 , had higher THM concentrations than the samples pre-oxidized with chlorine.

During Test 1B, THM formation potential may have been increased by KMnO_4 pre-oxidation due to incomplete oxidation of natural organic matter (NOM). Such a process could decrease the hydrophobicity of some NOM compounds by reducing them into smaller sub-units not as likely to adsorb onto PAC as the original NOM molecules. While experimental error due to factors discussed above could also account for the results, this explanation is plausible. For example, Waer and Vlastnik (1994) applied this reasoning, suggesting using pre-oxidation of NOM to increase the number of available adsorption sites on activated carbon for removing the resulting smaller taste and odor producing NOM molecules.

Other oxidants have been shown, under some conditions, to increase THM formation potential. As discussed by AWWA (1990), ozone often decreases THM formation potential, but under some circumstances, ozone can increase THM formation potential. Different water quality factors affect the results. As a result, AWWA (1990) strongly recommended pilot studies when ozone is proposed in the treatment train. Note that in some cases, pre-ozonation can stimulate removal of THM precursors through biological activity in anthracite and sand, and GAC filters. While ozone can be problematic in reacting with bromide to form THMs such as bromoform, AWWA (1990) notes that "Field studies have shown that the yield of bromoform is not significant unless the bromide level is high, for example, in certain groundwater and in seawater ozonated for control of biofouling in cooling towers." Nevertheless, most THMs formed during test experiments were brominated, suggesting that bromide concentrations and variations should be carefully examined if ozone is considered further as an oxidant at the Zai WTP. The formation of bromoforms can be minimized by lowering the pH of the water, or adding ammonia to the water, before ozonation.

Although KMnO_4 may have increased the THM formation potential in Test 1B, it still may be useful as an option at the IPS for aiding in taste and odor control. As discussed in the Test No. 4 section, KMnO_4 is often used for this purpose. Turbulence in the raw water pipeline

is substantial, such that it should be possible actual field results would be better than the test results. Increased oxidation beyond what was accomplished in Test 1B may not have the same effect on THM formation potential as suggested by the test results. In addition, effects of adding PAC to the regulating reservoir influent must be considered, as discussed in the Test No 4 section below. PAC addition at this point will markedly increase its effectiveness for removing both taste and odor compounds and THM precursors. Note further, that adding a KMnO_4 feeder at the IPS would add to plant operations flexibility, resulting in two KMnO_4 feed points for oxidation. Such flexibility is highly recommended (Kawamura, 1991), particularly under present circumstances.

The use of oxidants other than KMnO_4 for taste and odor control can be considered. Chlorine dioxide and ozone are both commonly used for this purpose in Europe, and North American use is increasing. However, note that "Of the common oxidants, ozone appears to be the most effective at destroying some of the recalcitrant taste and odor compounds particularly geosmin and 2-methylisoborneol (MIB), but all oxidants are limited in their effectiveness of taste and odor control." (AWWA, 1990)

Trends shown in Table C-2 indicate that THM formation peaked after about three days, declined, and then increased toward another maximum on Day 8. Some of these fluctuations may be due to instrumental error. (For quality control, a duplicate sample was submitted for analysis on Day 6. The result was quite reasonable.) It is possible that THM levels would have continued increasing beyond the eight days of monitoring. For Test 1A the Jordanian THM standard value of 150 ppb was exceeded within a few days, for Test 1B, the standard was exceeded within one day.

For Test 1C, the Jordanian THM standard was never exceeded. The chlorine residual concentration following the Test 1C treatment was slightly lower than for the other Test No 1 procedures. However, this small difference is not considered responsible for the fact that the Test 1C samples did not exceed the Jordanian THM standard. This result may also be explained by volatilization of THMs as discussed above. A high proportion of the relatively large THM concentration formed during the Test 1C incubation phase may have volatilized during the plant simulation jar testing. However, PAC adsorption may also have played a role in reducing THMs during the jar test phase. Another explanation is that the relatively high initial chlorine dose (2 ppm) oxidized organic matter to compounds less likely to form THMs than for potassium permanganate oxidation, for example. Note that such reactions would likely include formation of other, as yet unregulated in Jordan, chlorinated compounds, or total organic halogens (TOX), some of which, such as haloacetic acids, may be of health concern above certain concentrations.

Conclusions and Recommendations Regarding THMs and Raw Water Oxidation

The results indicate that preoxidation at the IPS with either chlorine or KMnO_4 can result in THM levels above Jordanian standards. It is likely that THMs formed during prechlorination simulations volatilized during subsequent experimental steps, contributing to experimental error. However, PAC adsorption of THMs and THM precursors may also have contributed to observed THM decreases. Nevertheless, the Jordanian THM standard of 150 ppb was exceeded for the prechlorination simulating high flow rates. For the low flow rate simulation, prechlorination did not result in THM levels exceeding Jordanian standards.

over the eight day monitoring period. This result was due to any of several factors (or combinations of these factors) volatilization of THMs initially formed, PAC adsorption of these compounds, oxidation of THM precursors by chlorine, formation of other TOX compounds such as haloacetic acids (HAA, of relatively recent health and regulatory concern), and/or experimental error.

The observation that KMnO_4 preoxidation resulted in higher THM concentrations than for prechlorination is similar to results sometimes obtained with ozone (AWWA, 1990). However, as suggested by the Test No. 4 results, KMnO_4 addition at the IPS can still be effective for taste and odor control without causing increases in THM levels. A second KMnO_4 feed point would add to operations flexibility. Higher turbulent mixing conditions in the raw water conveyance system could result in better results than in the laboratory tests. The resulting increases in oxidation may reduce the THM formation potential of the raw water, particularly in conjunction with PAC adsorption improvements when PAC feed is added to the regulating reservoir. Experimental uncertainty and the inability to perform statistical analyses must also be considered in evaluating the results.

Test No. 2 Nematode Inactivation

Introduction

Nematodes were found at the Zai WTP during investigations of the taste and odor problem. However, it is generally agreed that these phenomena are unrelated. At present, nematode counts in the raw water are low, although inactivated nematodes are sometimes detected in the finished water.

There is a consensus that no parasitic nematodes were ever detected. One major public health concern is that nematodes do ingest pathogens and therefore, can harbor viable cysts, shielding them from disinfection. Aesthetic concerns are also important. Nematodes are quite resistant to inactivation. Their ova (or eggs) are even more resistant than the larvae.

Recently, the staff began adding chlorine and KMnO_4 simultaneously at the chemical addition vault preceding the regulating reservoir (Chlorine is added at 1.6 - 2.0 mg/L, with KMnO_4 at 1.6 to 2.5 mg/L). Apparently, KMnO_4 alone did not inactivate nematodes, but adding both compounds appears to have a synergistic effect.

When KMnO_4 and chlorine are added simultaneously in this manner, it was found that chlorine residuals of 2 mg/L result in THM concentrations in the finished water of 65 to 80 ppb, with chlorine added at 1.6 - 1.7 ppm, THMs leaving the plant are about 40-50 ppb. One plant operations criterion is to try to keep finished water THM values at half the Jordanian standard of 150 ppb total THMs. Thus, adding the chlorine and KMnO_4 at reported levels does not appear to cause THM problems. However, the method of oxidizing simultaneously with chlorine and potassium permanganate apparently does not always result in elimination of live nematodes from the finished water. Further elaboration of these effects is expected by plant staff, once they have THM measurement capabilities and a new, functional TOC unit.

Chang, et al (1959) and Wei, et al (1969) studied nematodes in public water supplies. Very

high chlorine concentrations are generally ineffective at eliminating nematode viability. For example, Chang, et al (1959) found that 100 min in a hypochlorite solution containing 1.8 to 1.4 ppm free chlorine residual at a pH of 8.3 to 8.4 was insufficient to inactivate nematode larvae in their experiments. However, it was found that nematode removal by filtration is enhanced significantly by reducing or eliminating their motility through inactivation.

Test No. 2 procedures focused on effects of the following oxidants on nematode motility: KMnO_4 , chlorine, chloramines, and chlorine dioxide. A fifth examination of a mixture of KMnO_4 and chlorine was conducted because, as noted above, this approach is currently used at the plant.

Testing Procedure

Exhaustive efforts were made without success to locate more than one or two live nematodes at a time in the Amman area. Some nematodes were found at a nearby trickling filter plant. However, the low numbers of nematodes, and the fact that they were suspended in trickling filter effluent, which would exert an oxidant demand, ruled out this source. Additionally, nematodes were sought in the sediments of the KAC, but without success. Hence, all testing was performed using the nematode *Cephalobus*, from Carolina Biological Supply (Burlington, NC, USA). Stock solutions of 1,000 mg/L KMnO_4 and 1,000 free chlorine (made from Hypex, a 6.5% hypochlorite product discussed under Test No. 1 above) were used for testing.

A chloramine stock solution was produced by adding excess ammonium chloride to 100 mL of the 1,000 ppm stock chlorine solution. Attempts to measure the total chlorine residual of this solution were unsuccessful due to formation of a dark orange precipitate during the DPD measurement, suggesting interference by the excess ammonium chloride. Free chlorine residual values were zero and thus it was reasoned that added ammonia had been converted to combined chlorine. It was not possible to determine the distribution between mono-, di-, and tri-chloramine in the resulting solution. However, presuming all of the free chlorine present reacted such that only trichloramine resulted, the stock solution concentration was 2,300 mg/L chloramine. Note that the possibility of some ammonia toxicity of this solution cannot be ruled out at this time.

Chlorine dioxide (ClO_2) solutions were produced using an Aquamura water treatment kit provided by McNett Corporation (Bellingham, WA, USA). Instructions were followed to produce ClO_2 by combining equal volumes of the two solutions and adding distilled water. ClO_2 residuals were measured using the DPD ClO_2 method as in Standard Methods.

KMnO_4 and chlorine dosing experiments were performed using the first 'stock solution' of nematodes. This stock solution was produced by adding distilled water to a test tube containing potato plug growth medium and swirling the test tube. The resulting nematode slurry was placed in a separate test tube, and one ml was removed for counting. The remaining slurry was poured into 100 ml of canal water to make the stock nematode solution. Ten ml portions of this stock solution were added to beakers containing 100 ml of raw water. Four beakers were dosed to 10, 15, 20, and 25 ppm KMnO_4 , and four beakers were dosed to 10, 15, 20, and 25 ppm of chlorine. Two undosed control samples containing 10 ml of the nematode stock solution were also set up. The beakers containing the

nematodes and chemicals were mixed intermittently by swirling. One milliliter portion from each beaker was counted at recorded time intervals. All experiments with this stock nematode solution were performed at ambient temperature, 24.3 degrees C.

A second "stock solution" of nematodes was used for another set of experiments. For this solution, three test tubes of nematodes were used, creating a more concentrated solution of nematodes than the first stock solution. Fifteen ml portions of this stock solution were added to beakers containing 100 ml of canal water. Four beakers were dosed with 4.6, 23, 34.5 and 69 ppm chloramine using the stock solution discussed above. Another four beakers were dosed with 2 ppm KMnO_4 plus 1.5 ppm chlorine, 7 ppm KMnO_4 plus 5 ppm chlorine, 25 ppm KMnO_4 plus 25 ppm chlorine, and 15 ppm KMnO_4 plus 10 ppm chlorine. A control was also set up with no oxidant. The beakers containing the nematodes and chemicals were mixed intermittently by swirling. One ml portion from each beaker was counted at recorded time intervals. All experiments with this stock nematode solution were performed at ambient temperature, 22.6 degrees C.

Chlorine dioxide was produced in distilled water to concentrations of 0.8, 1.7, 8.8, and 5.0 ppm ClO_2 . The 1.7 and 5.0 ppm solutions were 200 ml, while the 0.8 and 8.8 ppm solutions were 100 ml in volume. Fifteen milliliters of the second nematode stock solution were added to each of these beakers. One milliliter portion from each beaker was counted at recorded time intervals.

A distilled water control was also run to determine effects of distilled water on the nematodes. *Cephalobus* were "extracted" from a test tube as described above, and eight ml of this extract were added to 100 ml of canal water to make a third nematode "stock solution". Ten ml of this third stock solution were added to 100 ml of distilled water. Nematodes were counted immediately and at the end of two hours as a check on effects of distilled water on the nematodes.

Results and Discussion

Results of the nematode inactivation studies are shown in Tables C-3 through C-8. All nematode counts in the table rows were obtained with 1 mL samples using a counting slide and microscope. Thus, the number alive and the number dead for each concentration and exposure time listed are for the same 1 ml sample. Following counting, each 1 ml sample was discarded.

The results help to understand relative effects of the different oxidation procedures on the *Cephalobus* nematodes. Extremely high concentrations of chlorine and KMnO_4 were required to inactivate very many nematodes. The combination of KMnO_4 and chlorine (Table C-6) was only effective at very high concentrations as well. These concentration levels are not practical.

Chloramines at high concentrations (Table C-5) were more effective than chlorine (Table C-3) or KMnO_4 (Table C-4). (Note that ammonia toxicity may have been a factor contributing to the toxicity of the chloramine solution used for this study.) Again, such high chloramine concentrations are not feasible.

Chlorine dioxide (Table C-7) at 17 ppm was effective at inactivating nematodes within a two hour period. Because the experiment was performed in a solution that was about 90% distilled water, the chlorine dioxide demand exerted was likely to have been somewhat lower than would be expected in canal water. (Note that the distilled water control test indicated that distilled water in itself did not affect nematode viability over the testing period.) Thus,

Table C 3
Nematode Inactivation Using Chlorine

Chlorine Concentration (ppm)	Exposure time (min)	No Alive	No Inactivated	Residual Chlorine after 240 min (ppm)
10	117	1	0	3.2
15	127	5	0	10
20	137	5	0	13
25	147	4	1	20
Control	98	7	0	-
10	204	4	4	3.2
15	222	4	0	10
20	237	5	1	13
25	247	4	4	20
Control	257	7	0	-

Table C-4
Nematode Inactivation Using KMnO₄

KMnO ₄ Concentration (ppm)	Exposure time (min)	No Alive	No Inactivated	Comments
10	110	4	0	
15	120	3	0	
20	130	2	1	
25	138	4	0	
Control	98	7	0	
10	204	4	1	
15	215	2	3	1 damaged, 2 yellow
20	223	1	2	
25	233	1	3	2 yellow
Control	204	3	0	

Table C 5
Nematode Inactivation Using Chloramine

Chloramine Concentration (ppm)	Exposure time (min)	No Alive	No Inactivated
4.6	180	27	23
23	169	7	29
34.5	173	3	45
69	193	2	48
Control	180	50-60	0
4.6	210	16	38
23	225	3	40
34.5	238	2	62
69	248	4	53
Control	230	50-60	0

Table C 6
Nematode Inactivation Using KMnO₄ And Chlorine

KMnO ₄ + Chlorine Concentrations (ppm)	Exposure time (min)	No Alive	No Inactivated
2 + 1.5	115	39	2
7 + 5	128	36	10
25 + 25	130	40	5
15 + 10	148	52	6
Control	130	50-60	0
2 + 1.5	236	29	1
7 + 5	245	23	19
25 + 25	238	16	36
15 + 10	285	28	26
Control	255	50-60	0

Table C 7
Nematode Inactivation Using Chlorine Dioxide

Chlorine Dioxide Concentration (ppm)	Exposure time (min)	No Alive	No Inactivated	Residual Chlorine Dioxide Concentration after 121 min (ppm)	Residual Chlorine Dioxide Concentration after 241 min (ppm)
0.8	110	25	1		0
1.7	121	3	15	1.8	1.0
5.0	121	0	23	4.6	2.7
8.8	108	0	51	5.8	3.9
Control	118	50/60	0	--	--
0.8	233	22	0	--	0
1.7	245	0	36	1.8	1.0
5.0	233	0	18	4.6	2.7
8.8	285	0	45	5.8	3.9
Control	250	50/60	0	--	--

nematode inactivation was probably greater than had concentrations been reduced by some chlorine dioxide demand exerted by constituents of the canal water. Given the short scope of the testing program, it was not possible to perform chlorine dioxide demand studies needed to understand this compound further.

Over a four hour period, the chlorine dioxide level decreased from 1.7 to 1.0 ppm. This chlorine dioxide concentration suggests that the U.S. EPA's proposed maximum value of 1.0 ppm for chlorite (ASCE, 1998) may have been exceeded.

Note that the turbulent conditions existing in the raw water pipeline would lead to much stronger mixing conditions than were possible during this study. Thus, it is anticipated that better inactivation would be achieved in the raw water main than during this simulation. In addition, chemical residuals in water reaching the plant would be lower than those measured during the laboratory study, again due to turbulence in the transmission main.

Conclusions and Recommendations Regarding Nematodes

Results for the *Cephalobus* nematode indicate that they will not be inactivated by $KMnO_4$ or chlorine, or a mixture of the two, at feasible concentrations within reasonable times. While chloramines at high concentrations were effective to some extent, only a very strong oxidant such as ozone can provide maximum assurance that nematodes will be inactivated. However, chlorine dioxide proved effective at inactivating the *Cephalobus* nematodes under these test conditions.

Concentrations of chlorine dioxide required for inactivating these nematodes may result in chemical concentrations of the by-product chlorite exceeding possible US EPA future recommended levels. Even if nematodes are inactivated or killed, however, they still may harbor pathogens, shielding them from disinfection.

Removal of nematodes can be maximized by optimizing all treatment steps. Applying water of minimum turbidity to the filters helps assure maximum removal prior to filtration. Currently the plant is upgrading its jar test apparatus to the more applicable square jar type. Plant personnel are performing many jar tests, and are evaluating various coagulants and different polyelectrolyte types and concentrations. It is important to approximate plant conditions with the jar test as closely as possible, making sure velocity gradients (G) and temperatures in the jar test apparatus are the same as within the plant coagulation and flocculation steps.

Maximizing filter performance is a key factor in removing nematodes. Improving sedimentation basin performance by eliminating the finger weirs and replacing them with baffle walls will improve sedimentation performance. Adding polyelectrolyte filter aid and filter conditioner during the last few minutes of backwashing will result in lower filter turbidities. An air scour system will provide improved media cleaning for more effective performance.

Test No 3 - Jar Testing

Introduction

The object of the jar tests were to compare aluminum sulfate (alum, (used presently at the plant) with the alternative iron salt coagulants, ferric sulfate and ferric chloride. Prior to most of the jar tests, oxidation of raw water at the IPS was simulated using KMnO_4 doses matching those in use at the plant at the time. Then, plant simulations were performed in the jars using chemical dosages in use at the time of testing.

ASCE (1998) noted that optimum pH values vary for alum and ferric salts, and listed pH ranges within which alum and ferric salt coagulation can generally be optimized. For alum, this pH range is from 5.5 to 7.5 (typically 7.0), while for ferric salts, the pH range is from 5.0 to 8.5 (typically 7.5). Note that optimum coagulant and coagulant aide concentrations as well as optimum pH values are best determined by jar testing and observations of plant performance.

Jar tests were performed using an old, impeller type of jar test device. This unit required slightly higher mixing speeds than the more modern unit used for process control jar testing at the Zai WTP. All jar testing was performed in one-liter beakers. At present, plant personnel are planning to build the square type of mixing vessels, which can be used to more closely match rapid mixing and flocculation stage mixing characteristics. It was not possible to study the many variables affecting jar test (and plant) results, such as mixing speeds and durations, and temperatures. Results can be used for comparative purposes, however, because testing conditions were kept as identical as possible for comparing alum, ferric sulfate, and

ferric chloride

At present, plant personnel are conducting numerous jar tests for process control, with alum as the chief coagulant. While alum appears to be serving well (both functionally and economically), there may be problems associated with aluminum solubility. The Jordanian standard for dissolved aluminum is 0.1 with a maximum of 0.2 ppm. (The maximum level suggested in the US is 0.05 ppm. This suggested level is not a requirement, but rather is a preferred goal.) Plant jar tests run in concert with dissolved aluminum determinations are revealing that normal alum doses resulting in good coagulation and flocculation do not suppress pH values enough to lower aluminum solubility to desired levels. Hence, plant staff are experimenting with increasing alum doses for lowering pH values such that aluminum solubility is reduced.

It is recognized that increased coagulant doses can also be used to remove Total Organic Carbon. This approach is being developed in US regulations (where it is termed "enhanced coagulation") for reducing THM formation potential. However, use of sulfuric acid for pH suppression is being investigated in terms of treatment effectiveness and costs. Once laboratory total organic carbon (TOC) and THM instruments are up and running, the plant staff will be targeting and optimizing the various interrelated treatment objectives.

Note that pH values favorable for reducing alum solubility and/or for optimizing alum coagulation can be corrosive to distribution systems. For this reason, pH values often are subsequently increased, further adding to chemical and labor expenses. This factor further favors ferric salts which are usually effective at higher pH values than alum, without posing aluminum solubility problems, or necessitating the initial downward adjustment of pH and final upward adjustment of the pH in the treated water to avoid corrosivity and colored water problems in the distribution system.

Testing Procedure

Ferric sulfate, ferric chloride, and alum were compared in a set of tests on a sample of raw water taken from the KAC intake. The plant laboratory stock alum solution used was 10 g/L. A 10 g/L stock ferric sulfate (as tetrahydrate, that is, $\text{Fe}_2(\text{SO}_4)_3 \cdot 4\text{H}_2\text{O}$) solution was made for testing using reagent grade ferric sulfate purchased from Fisher Scientific.

A ferric chloride stock solution was made by diluting the 40% (nominal concentration) ferric chloride solution on-hand. Label information on this solution was as follows: FR-1410 Ferric Chloride, Made in India, supplied by Saleh and Abdulaziz Abahsain Co., Ltd (Chemicals Division), P O Box 209, AL Khobar 31952, Saudi Arabia. The resulting stock solution for jar testing was 6.88 g/L ferric chloride and had the same iron concentration as the ferric sulfate stock solution.

Raw water characteristics were measured before testing. For each coagulant, six one liter samples of raw water were dosed with 2 ppm KMnO_4 (as used at the plant at the time) and kept in the dark for 195 minutes (the nominal time for raw water to reach the plant at the time of testing). While stirring at 115 rpm, coagulant was added in varying amounts, along with 1.5 ppm cationic polymer and 20 ppm PAC. The samples were stirred at 115 rpm for one minute, followed by slow mixing at 44 rpm for 20 minutes. Then the anionic

polyelectrolyte was added at 0.01 ppm, followed by another 10 minutes of slow mixing at 44 rpm. Mixing was then stopped. Following a 30 minute settling period, turbidity and other properties of the settled water were measured.

Two other jar test sets were run using raw water at the plant tap, which had $KMnO_4$ added at the regulating reservoir (and a low dose of copper sulfate added at the IPS). One jar test set involved adjusting the pH of raw water in six one liter beakers from 8.59 to 7.58 using sulfuric acid. Then, the jar tests were run as above. Another jar test set was run in an attempt to optimize the cationic polyelectrolyte dosage used with ferric sulfate. This test involved using the best ferric sulfate dosage previously determined, and different cationic polyelectrolyte concentrations. Other chemical additions and mixing procedures were then carried out as described above.

Results and Discussion

Initial raw water properties were as follows:

Table C 8
Raw Water Characteristics

Property	Value
Turbidity	21.6 NTU
Alkalinity	190 mg/L
pH	8.44
Temperature	21.6

Results of the initial coagulant tests, which included preliminary oxidation with $KMnO_4$, are shown in the following three Tables C-9 through C-11.

Table C 9
Jar Test - Ferric Sulfate Coagulant

Ferric Sulfate Concentration (ppm)	Turbidity (NTU)	pH	Alkalinity (mg/L)	Temperature (Degrees C)
20	1.55	7.97	166	21.5
25	1.05	7.89	160	21.4
30	1.29	7.8	162	21.5
35	1.30	7.69	160	21.4
40	1.35	7.61	160	21.4
45	1.15	7.56	150	21.4

Table C 10
Jar Test - Alum Coagulant

Alum Concentration (ppm)	Turbidity (NTU)	pH	Alkalinity (mg/L)	Temperature (Degrees C)
30	0.45	7.73	162	21.6
35	0.78	7.83	160	21.4
40	0.75	7.69	160	21.6
45	0.72	7.64	156	21.4
50	0.55	7.59	150	21.5
55	0.81	7.52	150	21.6

Table C-11
Jar Test - Ferric Chloride Coagulant

Ferric Chloride Concentration (ppm)	Turbidity (NTU)	pH	Alkalinity (mg/L)	Temperature (Degrees C)	Comment
14	0.70	7.82	164	21.9	
17	0.44	7.66	156	21.8	
21	0.33	7.52	154	21.8	
24	0.30	7.48	146	21.9	yellowish
28	0.37	7.42	146	21.9	yellowish
31	0.27	7.35	146	22.1	yellowish

All three coagulants reduced turbidity levels below the U.S. guideline maximum of 2 NTU (UAEPA, 1991) before filtration. However, minimizing turbidity applied to filters is an important treatment goal, such that values well below 2 NTU should be obtained if possible. Ferric chloride and alum reduced turbidity levels to a greater extent than ferric sulfate during testing.

Under the jar test conditions, ferric chloride functioned best, although above 21 ppm the settled water was yellowish in color. Ferric chloride suppressed pH values more than the other coagulants, although this effect was a small one. This may have been due to the fact that the ferric chloride solution on hand was reported to contain acid.)

Alum functioned best at 30 and 50 ppm. However, the 30 ppm result appears anomalous because this alum dose should have resulted in the least pH suppression compared to the other dosages. The 50 ppm alum dose functioned well, and is in line with current use (except when alum concentrations are increased to reduce aluminum solubility). Ferric sulfate

worked reasonably well, but not as well as alum or ferric chloride under test conditions. At concentrations resulting in maximum turbidity levels, ferric sulfate did not suppress settled water pH values to the same extent as the other two coagulants. It is not known whether the ferric chloride solution used in the canal (and used for these tests) is approved for potable purposes.

Results for the ferric sulfate jar testing with varying cationic polyelectrolyte doses is shown in Table C-12.

Table C-12
Jar Test Ferric Sulfate With A Cationic Polyelectrolyte Aid

Ferric Sulfate Concentration (ppm)	Cationic Polyelectrolyte Dose (ppm)	Turbidity (NTU)
25	0.0	1.10
25	0.2	1.6
25	0.4	1.1
25	0.8	1.4
25	1.2	1.6
25	1.5	1.25

As noted above, this testing was performed using raw water as it exits the regulating reservoir. The ferric sulfate dose was 25 ppm, which gave the lowest settled water turbidity during the initial ferric sulfate jar test. Other chemical dosages were as at the plant at the time of testing: PAC dosing was at 22.5 mg/L, and anionic polyelectrolyte dosing was at 0.08 ppm. Further bench scale or full-scale testing with different (lower perhaps) ferric sulfate doses and perhaps slightly higher polyelectrolyte doses could result in a more cost-effective coagulant and aid combination. At the city of Los Angeles' Aqueduct Filtration Plant for example, the polyelectrolyte is the primary chemical and ferric chloride is the coagulant aid.

The results indicate that the cationic polyelectrolyte currently in use is not nearly so effective a coagulant aid with ferric sulfate as it is with alum. Dr. Murad Jabay Bino is in contact with Allied Colloids (and perhaps other polyelectrolyte manufacturers) and further jar tests are planned in an attempt to identify a more effective coagulant aid (or aids) for ferric sulfate.

Results of the alum jar testing with pH adjustment are summarized in Table C-13.

For this pH adjustment test, the raw water turbidity was 13.4 NTU, alkalinity was 180 mg/L, pH was 8.59, and the temperature was 24.8 degrees C. The initial pH was lowered from 8.59 to 7.58 prior to testing. PAC was dosed at 20 ppm, cationic polyelectrolyte at 1.5 ppm, and anionic polyelectrolyte at 0.01 ppm. Mixing conditions were the same as used for all Test No. 3 jar testing.

Table C 13
Jar Test - Alum Coagulant With pH Adjustment

Alum Concentration (ppm)	Turbidity (NTU)	pH	Alkalinity (mg/L)	Temperature (Degrees C)
10	1.02	7.58	155	22.0
20	0.60	7.58	150	21.9
25	0.49	7.55	150	21.9
30	0.48	7.52	150	21.9
40	0.33	7.42	142	21.9
50	0.45	7.33	140	21.9

The alum results with pH adjustment was somewhat better than without pH adjustment. However, different raw water samples were used for the two jar test sets, such that this result could be due to differing raw water characteristics. In addition, the water temperature was greater during the pH adjustment jar test than during the initial testing. Thus, water viscosity was less during the pH adjustment test than when pH values were not adjusted, favoring higher particle velocity settling and hence promoting lower settled water turbidities.

Optimum turbidity removal was at 40 ppm alum. The final pH was lower when alkalinity was reduced with sulfuric acid first than when alkalinity was reduced by alum alone. In addition, sulfuric acid addition resulted in final pH value (at the lowest turbidity) within the range of optimums generally found for alum (5.5 to 7.5) as reported by ASCE (1998). These results indicate that pH adjustment with sulfuric acid can lower alum requirements.

Note also that decreased final pH values are helpful (within limits) for reducing aluminum solubility. However, corrosion phenomena in distribution systems can be problematic when pH values are too low. A minimum pH value of around 7.8 is often considered necessary in distribution systems to prevent copper dissolution from piping, for example. Thus, the sulfuric acid approach could necessitate addition of a base to bring pH values back up somewhat. Base addition also could be needed if high alum doses are used to suppress pH values, and if ferric chloride is used as well. Optimizing ferric chloride addition appears to be a better approach than altering pH values with sulfuric acid when using alum. The use of ferric sulfate avoids the use of either acid and base pH adjustments.

Cost estimates for the using the three coagulants are shown in Table C-14. Note that the costs are based on the plant running at full capacity (123,000 m³/d).

Clearly, alum is much less expensive than the other coagulants at the dosages and prices shown. However, costs associated with alum will increase should pH adjustment be practiced. As discussed above, such pH adjustment could be both downward to optimize coagulation and to minimize aluminum solubility, and then upward to reduce corrosivity. Other sources of ferric salts may be found, with better prices.

Table C 14
Comparative Coagulant Costs

Coagulant	Unit Cost (JD/Tonne)	Dosage (ppm)	Estimated Daily Cost at Full Capacity (JD)
Alum (as currently used)	200	50	1,107
Ferric chloride (solution, on-hand)	950	24	2,804
Ferric sulfate (tetrahydrate)	965	25	2,967

Conclusions and Recommendations Regarding Coagulants

Jar test results indicate the ferric salts work reasonably well. Under test conditions, ferric chloride worked better than ferric sulfate or alum, and suppressed pH values somewhat more than did the other coagulants. Alum worked better under test conditions than ferric sulfate using the coagulant aides available. Slightly high doses (above optimum) of the ferric chloride solution studied imparted a yellow color to the settled water.

Efforts to use acid for lowering pH values with alum may help both coagulation and with decreasing aluminum solubility, however, some caustic (or lime or soda ash) may have to be added later to prevent corrosion problems in the distribution system. It is likely that ferric sulfate would function better with a different polyelectrolyte than the one in use with alum, plant staff are currently seeking alternative coagulant aides for further jar testing with ferric sulfate. Current cost data indicate that alum is much less expensive than the other two coagulants. However, if pH adjustment(s) is needed for alum, total costs associated with alum use will increase.

If ferric sulfate is used, it is recommended that jar testing be performed to find alternative polymer coagulant aids and doses for use with different ferric sulfate doses.

Ferric chloride may also be considered as well. Potable applicability of the ferric chloride on hand should be confirmed and further jar testing should be performed to understand any color changes. Capital costs of ferric chloride storage, feed (and backup feed), etc. all must be considered in terms of switching to ferric chloride. Base addition will be necessary for corrosion control if pH values are suppressed too far by ferric chloride.

Test No 4 - PAC Testing

Introduction

This test targeted testing two improvements for taste and odor control at the plant providing a potassium permanganate feed system at the influent pump station (IPS), and PAC feed at the regulating reservoir influent. (It was assumed for purposes of this test procedure that the regulating reservoir will be baffled such that its flow regime approaches plug flow.)

Note that this testing was performed after the taste and odor episode in the summer of 1998. Thus, the test conditions cannot indicate precise means for addressing a problem event of this kind. However, information about the relative effects of new potassium permanganate and PAC feed locations can be learned.

A number of aspects of chemical oxidation for taste and odor control at the Zai plant were discussed under Test No 1. Chemical oxidation is commonly practiced for addressing taste and odor as well as other problems, and potassium permanganate is often used in this application. However, oxidants are not always effective at taste and odor control and can impart taste and odors themselves. In addition, as suggested by the Test No 1 results and in the literature, preoxidation can in some circumstances increase THM formation potential. In any event, oxidant feed at the IPS will add significantly to plant operations flexibility for addressing future taste and odor episodes. Activated carbon is also very important for addressing taste and odor problems at the Zai WTP, and providing an improved feed point for PAC will significantly enhance taste and odor reduction.

Use of PAC for taste and odor control was reviewed in some detail by ASCE (1998), and concepts from this design text follow. PAC contact time should be at least 15 minutes. Further, it has been reported that even longer contact times than 15 minutes can be required for adsorption of 2-methylisoborneol (MIB) and geosmin. These compounds are commonly associated with offensive odors caused by certain algae, and can be difficult to oxidize. PAC should be fed prior to addition of coagulants because they can coat the surface of PAC particles, inhibiting mass transfer to carbon adsorption sites.

Total Odor Number (TON) testing at the Zai WTP is performed by operators on a regular basis. Dilutions are performed using distilled water.

Interest has been expressed in alternative treatment of canal water prior to the intake. Kawamura (1991) discussed chemical treatment methods useful for algae control. Copper sulfate can be added in dosages ranging from 0.05 to 0.8 ppm, depending on algae species, potassium permanganate dosages from 0.4 to 5 ppm can be effective, and free chlorine residuals of 0.2 - 1 ppm can control algae. However, chlorine residuals are difficult to maintain when organic matter is present, and sunlight increases chlorine dissipation. Potassium permanganate is not usually used in water reservoirs due to its cost and resulting purple to pink color. Use of natural treatment methods such as different fish species requires careful evaluation by limnologists and aquaculture experts.

Testing Procedure

The test was a treatment simulation procedure similar to Test 1B described previously. Six one-liter raw water samples were dosed with 2.3 ppm potassium permanganate and held in the dark for 3.3 hours (the nominal detention time in the raw water piping system at the time of testing). Then, one liter beakers were dosed with 3, 6, 9, 12, 15, and 18 ppm PAC followed by gentle agitation with the jar test apparatus for 129 min (the detention time in the regulating reservoir at the time of testing).

Next the jar contents were treated using essentially the same procedure as for Test No. 1, adding during rapid mixing at 115 rpm alum at 45 ppm plus cationic polyelectrolyte at 1.5 ppm, followed by one minute of rapid mixing. Then the mixing speed was reduced to 44 rpm for 20 min, followed by addition of 0.01 ppm anionic polyelectrolyte. After another 10 min of slow stirring, mixing was turned off. Following 30 min of settling, the settled water was removed from each beaker and the chlorine residual was adjusted to 0.8 ppm using the chlorine stock solution from Test No. 1. Next, each sample was filtered as in Test No. 1, followed by addition of chlorine from the stock solution to a residual of 1.45 ppm, matching the value in the finished water at the time.

Then, TON flasks were set up for each sample, and for raw and finished water samples taken at the time of testing. In consultation with operators on shift at the time, who reported a TON of 1 for the finished water, dilutions were set up only for the raw water sample TON determination. (Note that dilutions are performed with distilled water.) It was learned that finished water TON values were considered to be 1 if the only odor detected was that of chlorine. As in Standard Methods, sodium thiosulfate is generally added by plant staff at that point to suppress the characteristic chlorine odor to confirm it is the only odor constituent.

After the TON flasks reached 60 degrees C, the bottles were sniffed. It was ascertained that the only odor present in all the flasks was the characteristic chlorine odor. The odor level was the same in each flask. Therefore, the sample with the lowest PAC dose (at 3 ppm) was reserved for long-term odor examination. This flask and the finished water odor flask were stored at room temperature except when odor testing was performed at 60 degrees C over a three day period.

A sample from each jar test and one finished water sample were set up for THM testing three days later. THM samples were stored at 28 degrees C as discussed for Test No. 1, to simulate worst-case temperature conditions.

A second test was conducted simulating simultaneous addition of KMnO_4 and PAC prior to the regulating reservoir. The test was run as above, using the same PAC dosages as above, and other chemical additions as at the plant at the time of testing. These chemical additions were 1.73 ppm KMnO_4 , 59.5 ppm alum, 1.77 ppm cationic polyelectrolyte, and 0.011 ppm anionic polyelectrolyte. The residual chlorine before testing was adjusted to 1.2 ppm (as opposed to 0.9 ppm within the plant), and to 1.3 ppm after filtration. Odor tests were set up as above for the sample with 3 ppm PAC and plant effluent at the time of testing. No THM tests were performed for this second experiment.

Results and Discussion

For both tests, the TON of the raw water was 12, and that of the finished water was 1. The odor of the first water sample dosed initially with 3 ppm PAC was followed daily for three days. No discernible change was detected in this sample's odor. The plant finished water sample held in the same manner also did not change. At the end of the three day period, even the characteristic chlorine odor had dissipated, and chlorine residuals were found to be zero.

Therefore, the results indicate that preoxidation with $KMnO_4$ followed by 3 ppm PAC before coagulation was at least as effective as plant procedures at the time of testing. Within the plant, 20 ppm PAC was being added just prior to the coagulation step. As noted above, this location is not recommended because it both binds adsorption sites and inhibits mass transfer to the sites. However, it is difficult to extrapolate this result to the taste and odor compounds responsible for the summer episode. These compounds may respond differently to preoxidation and may have different adsorption characteristics than the compounds responsible for the relatively minor odor at the time of testing.

THM testing results following three days of storage are shown in Table C-15.

**Table C-15
PAC Versus THM Formation**

Carbon Dose, ppm	THM concentration after 3 days, ppb
20 (Plant finished water)	198
3	111
6	79.6
9	131
12	160
	161
15	81
18	186

The plant finished water sample had the highest THM concentration of all samples taken, and was above the Jordanian regulatory level of 150 ppb. Thus, the combination of oxidation at the IPS and PAC addition at the regulating reservoir appears to result in less THMs than the current configuration. However, THM volatilization during testing may have influenced this result, somewhat.

The Test No. 4 jar test samples did not show a clear THM trend. Most samples were close to or below the Jordanian maximum allowable THM value. As discussed for Test No. 1,

non-uniform THM volatilization during the different treatment steps, and experimental error, contributed to variability of the results. However, unlike Test 1B, when PAC was added just prior to coagulation, PAC added well before coagulation in Test No. 4 is likely to have had a beneficial effect. PAC added in Test No. 4 was readily available to adsorb THM precursors in spite of potential adverse effects of preoxidation on THM formation potential. Thus, Test No. 4 THM levels at three days were below the Test 1B THM result (except for the 18 ppm PAC sample) after three days of storage. This result may also have been due to the fact that the initial chlorine residual was lower in Test No. 4 than in Test 1B (1.45 ppm versus 1.60 ppm). However, at these chlorine residual levels, the correlation between chlorine concentration and THM formation is not a strong one.

The second TON test gave odor results similar to the first. The sample with the least amount of PAC (3 ppm) had a chlorine odor that was indistinguishable from the plant finished water sample taken at the same time. Both samples had only the characteristic chlorine odor noted above. When sodium thiosulfate was added as in Standard Methods, neither sample had a discernible odor. Thus, under test conditions, simultaneous addition of KMnO_4 and 3 ppm PAC prior to coagulation was as effective as the plant practice of adding 20 ppm PAC. Note, however, that at that time the plant was adding a very high alum dose (59.5 ppm). This high alum dose may have resulted in removal of more NOM responsible for some taste and odor than at the 45 ppm alum dose previously in use.

Conclusions and Recommendations Regarding PAC and KMnO_4 Addition

The results indicate that the combination of KMnO_4 oxidation at the IPS followed by PAC addition at the regulating reservoir will require less carbon than used at present for taste and odor control. In fact, it is possible that with a long preoxidation stage, PAC may not be required for taste and odor control under present conditions. However, it is difficult to extrapolate these results to the compounds responsible for the summer taste and odor episode, which may have different oxidation and adsorption properties.

In the simulations of KMnO_4 addition at the IPS, adding PAC well before the coagulation stage resulted in less THM formation than when PAC is added just before coagulation. Thus, it is likely that PAC addition as at the regulating reservoir removed THM precursors, regardless of whether KMnO_4 increased THM formation potential as suggested by the Test No. 1 results.

The experiment with adding KMnO_4 and PAC simultaneously also indicated that adding PAC well before coagulation lowers PAC dosage requirements. However, effects on THM or TOX formation were not determined for this experiment.

These observations bolster the recommendation of adding a KMnO_4 feeder at the IPS, and adding PAC at the (baffled) regulating reservoir. This arrangement will provide added operational flexibility to respond to the next taste and odor episode.

Because it was not possible to run these tests with the problem water, it appears necessary to provide PAC feed capability comparable to that found necessary during the event. This approach will be a conservative one, of course. Two carbon feeders, each feeding from zero to 35 ppm carbon at current flow rates could be used. This approach would provide a

maximum of 70 ppm PAC, which was found adequate during the taste and odor event. The feeders should be piped to maximize operations flexibility. Decisions would have to be made later in terms of needs for more carbon feed capacity after the plant capacity is doubled, data gathered over the near term will aid with that decision-making.

If GAC is added to the filters, then a 70 ppm PAC feed capability will of course not be necessary. However, the lifetime of GAC for taste and odor control cannot be known precisely. Careful monitoring of the carbon in the filters will be necessary if this route is taken. GAC may present some cost savings over PAC feed in the long run.

Regarding the KMnO_4 feed concentration at the IPS, dosage ranges from 0.5 to 5 mg/L are usual for KMnO_4 feed (Kawamura, 1991). Note also that 0.6 to 1.2 mg/L KMnO_4 is often all that is necessary to remove taste and odor compounds (Kawamura, 1991).

Other oxidants may be considered, such as chlorine dioxide and ozone, for removing taste and odor compounds. These oxidants should be considered for long-term upgrading of plant facilities.

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APPENDIX D

MANUFACTURER'S CHLORINE DIOXIDE SYSTEM

RIO LINDA CHEMICAL COMPANY'S CHLORINE DIOXIDE SYSTEM



**THE SOLUTION
FOR
WATER TREATMENT**

CHLORINE DIOXIDE

Chlorine dioxide (ClO₂) is a yellow-green gas similar in appearance and odor to chlorine. Unlike chlorine, chlorine dioxide gas cannot be compressed and bottled. Consequently, chlorine dioxide must be generated on-site.

Prior to the introduction of Rio Linda Chemical Company's (RLC's) chlorine dioxide system, industry

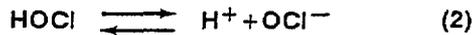
standard was to generate chlorine dioxide using chemical feed pumps to add acid and sodium chlorite to a solution of chlorine (chlorine/chlorite/acid system). Typical yield* for this type of generator is 80-90%. Rio Linda Chemical Company discovered a way to increase the chlorine dioxide yield to 95-98% without using acid or chemical feed pumps.

The Chemistry of Chlorine Dioxide**

When chlorine gas is dissolved in water, it rapidly hydrolyzes (actually reacts with the H₂O molecule) to form hypochlorous acid:

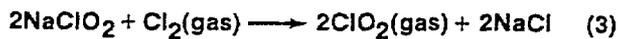


The further dissociation of hypochlorous acid follows to produce hypochlorite ion:

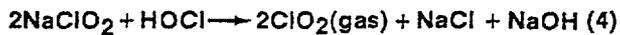


The pH of the water into which the chlorine gas is dissolved determines the speciation of chlorine, as shown in Figure 1 for a 0.05 M chlorine solution (this is the highest chlorine concentration encountered in typical installations).

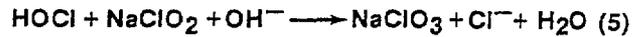
The reactions that generate chlorine dioxide from chlorine and sodium chlorite are:



and



There are also some undesirable side reactions that can take place in the generation of chlorine dioxide. These reactions consume sodium chlorite and produce an undesirable reaction by-product, sodium chlorate:



and



Reaction (3) is extremely fast, as compared to reaction (4), which is about 100 times slower. Reactions (5) and (6) become important in dilute solutions. The ideal situation from the standpoint of maximizing chlorine dioxide yield is to select reaction conditions to promote reaction (3) and minimize reactions (5) and (6). With our fundamental understanding of chlorine dioxide chemistry, Rio Linda Chemical Company has done just that. We manufacture chlorine dioxide generating systems based on sound chemical principles. Our systems simplify chlorine dioxide generation, achieve yields approaching the theoretical maximum, and are virtually maintenance free.

RELEVANT CHLORINE SPECIES

CHEMICAL FORMULA	NAME
Cl ₂	Molecular chlorine (gas)
HOCl	Hypochlorous acid
OCl ⁻	Hypochlorite ion
Cl ⁻	Chloride ion
NaClO ₂	Sodium chlorite
NaClO ₃	Sodium chlorate
ClO ₂	Chlorine dioxide (gas)

TABLE I

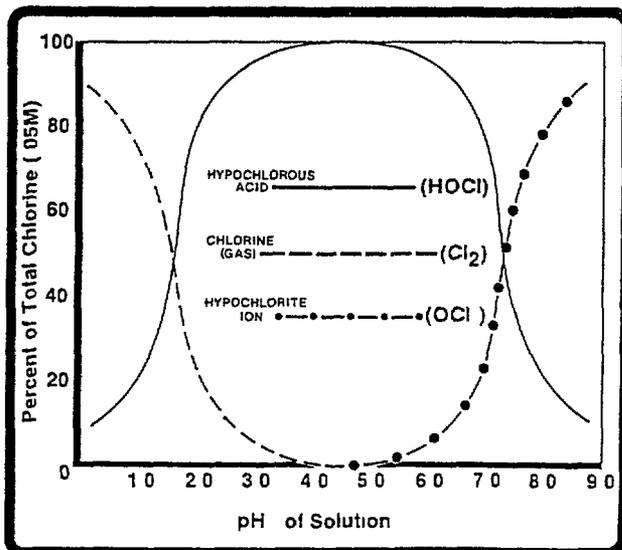


FIGURE 1

Yield defined as conversion of sodium chlorite to chlorine dioxide. Relevant chlorine species for this discussion are shown in Table I.

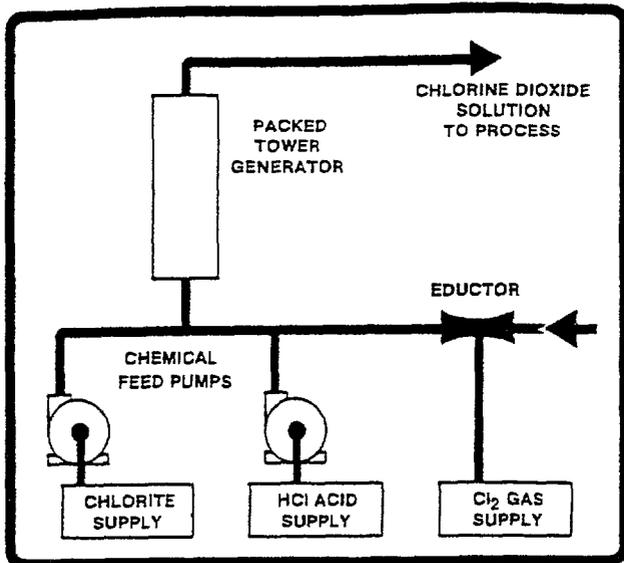


FIGURE 2

THE COMPETITION

To illustrate the counterproductive nature of our competitors' systems, consider this the chlorine/chlorite/acid systems (Fig 2) require the use of acid (some use excess chlorine in place of acid) to increase the relative concentration of hypochlorous acid and molecular chlorine in the eductor water (see reactions 1 and 2) Figure 1 illustrates the fact that even at pH 2 most of the chlorine is still hypochlorous acid which promotes the slower reaction (4) instead of reaction (3) Furthermore these systems feed the concentrated sodium chlorite solution into the chlorine water stream where it is diluted before it can react with the chlorine These conditions force reaction (4) to compete with reactions (5) and (6) for the sodium chlorite thereby decreasing chlorine dioxide yield and forming the undesirable reaction by-product sodium chlorate

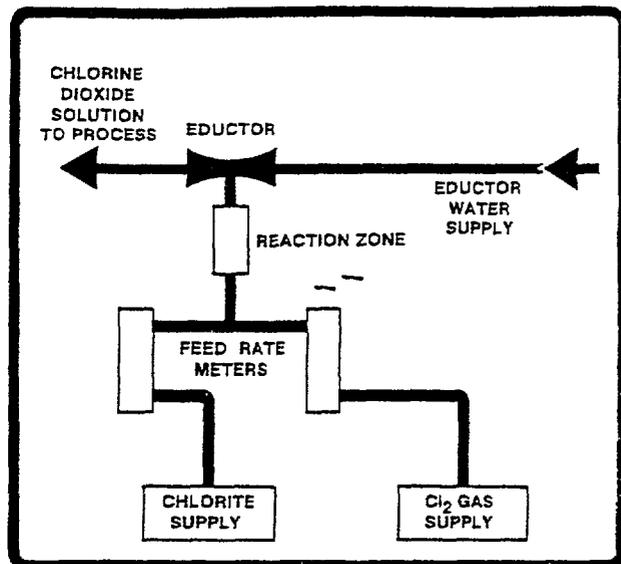


FIGURE 3

OUR SYSTEM

In contrast the RLC patented reactor brings the concentrated sodium chlorite solution into contact with molecular chlorine gas in such a way that the only reaction that takes place is the substantially instantaneous reaction (3) which yields only chlorine dioxide (see Figure 3) Since the molecular chlorine gas and concentrated sodium chlorite react before dilution reactions (5) and (6) are completely suppressed The pure chlorine dioxide gas is then dissolved into a water stream ready for use—uncontaminated by costly competitive reaction by-products by excess chlorine or by acid We provide a simple and efficient system that achieves a 95 to 98% yield—and that means more chlorine dioxide for your dollar

Economy

This revolutionary 2-chemical process does not require acid addition and does not require chemical feed pumps, this results in lower operating costs less maintenance and simplified control

High Yield

An immediate and complete reaction occurs yielding a continuous 95 to 98% conversion of sodium chlorite to chlorine dioxide The high yield insures a pure product uncontaminated with chlorine or other by-products This results in reduced chemical costs

Safety

The chlorine-chlorite reaction takes place under vacuum insuring maximum safety and simplicity of operation Both the chlorine gas and the sodium chlorite solution are educted into the reaction column The system automatically shuts down if eductor water supply fails or if chemical feed lines break

Rio Linda Chemical Company has a national and international reputation as a supplier of high performance chlorine dioxide systems Our patented process for generating chlorine dioxide provides consistently high yields and does so more cost efficiently than any other equipment on the market today So no matter what your application for chlorine dioxide Rio Linda Chemical Company's engineering staff can custom design a chlorine dioxide system to fit your needs

If you want a simple and economical method for generating chlorine dioxide, talk to Rio Linda Chemical Company—
we can save you money!

Cost Comparisons

To illustrate the savings of the RLC Chlorine Dioxide System consider the following conditions

Flow Rate	25 MGD
Chlorine dioxide dose	3 ppm
Sodium chlorite	25% solution
Chlorine dioxide usage	625.5 lbs ClO ₂ /day
Sodium chlorite consumption at 95% yield	336 gals/day
Sodium chlorite consumption at 85% yield	376 gals/day

SODIUM CHLORITE SAVINGS

40 gals/day
= \$200/day
= \$6,000/month
= \$72,000/year

AND THIS DOES NOT EVEN INCLUDE THE SAVINGS FROM NOT ADDING ACID!

FOR WHATEVER REASONS YOU ARE CONSIDERING CHLORINE DIOXIDE

- DRINKING WATER DISINFECTION AND THM CONTROL
- TASTE AND ODOR CONTROL
- IRON AND MANGANESE CONTROL
- MICROBIOLOGICAL CONTROL OF COOLING WATER
- WASTEWATER DISINFECTION
- PULP BLEACHING
- DISINFECTION AND SANITATION IN FOOD PROCESSING

Rio Linda Chemical Company's Chlorine Dioxide System can save you money!

RIO LINDA CHEMICAL CO , INC

2444 ELKHORN BLVD
RIO LINDA, CA 95673

(916) 991-4549

(916) 991-3071

TELEX 171-388

APPENDIX E

GIARDIA AND VIRUS INACTIVATION CT TABLES

TABLE E-8
 CT VALUES FOR
 INACTIVATION OF GIARDIA CYSTS
 BY CHLORINE DIOXIDE

<u>Inactivation</u>	<u>Temperature (C)</u>					
	<u><=1</u>	<u>5</u>	<u>10</u>	<u>15</u>	<u>20</u>	<u>25</u>
0.5-log	10	4.3	4	3.2	2.5	2
1-log	21	8.7	7.7	6.3	5	3.7
1.5-log	32	13	12	10	7.5	5.5
2-log	42	17	15	13	10	7.3
2.5-log	52	22	19	16	13	9
3-log	63	26	23	19	15	11

TABLE E-9
 CT VALUES FOR
 INACTIVATION OF VIRUSES
 BY CHLORINE DIOXIDE pH 6-9

<u>Removal</u>	<u>Temperature (C)</u>					
	<u><=1</u>	<u>5</u>	<u>10</u>	<u>15</u>	<u>20</u>	<u>25</u>
2-log	8.4	5.6	4.2	2.8	2.1	1.4
3-log	25.6	17.1	12.8	8.6	6.4	4.3
4-log	50.1	33.4	25.1	16.7	12.5	8.4