AN INNOVATIVE APPROACH TO URBAN WASTEWATER TREATMENT IN THE DEVELOPING WORLD

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ABSTRACT

Should cities of the developing world invest in the dominant municipal wastewater treatment technology of Western Europe and North America --- conventional primary plus activated sludge? Or, are there alternative "sustainable sanitation" approaches? This paper discusses these issues and makes a specific technological proposal --- the adoption of recent innovations in chemically enhanced primary treatment, known as CEPT, as the appropriate first step in urban wastewater management.

Why is CEPT a superior choice?

• CEPT uses small doses of coagulant salts and flocculant polymers to produce a highly efficient, single stage treatment process that is superior in terms of suspended solids and organic carbon removal to conventional primary treatment alone, but also, in terms of phosphorus removal and energy consumption, to conventional primary plus activated sludge.

• CEPT, because of enhanced settling, results in increased treatment capacity and removal efficiency. As has been demonstrated by retrofitting some of California’s largest conventional primary plants, CEPT provides a low-cost way of quickly upgrading overloaded plants.

• New CEPT plants can take advantage of enhanced settling to increase the surface overflow rate and reduce the number of settling tanks. When Hong Kong’s new plant switched from conventional primary to CEPT, in the design stage, the number of settling tanks was reduced to two-thirds. In Mexico City it is estimated that capital and O & M costs for CEPT would be about 55% of the cost of conventional primary and secondary biological treatment, including sludge handling.

• CEPT effluent, in contrast to conventional primary effluent, can be effectively disinfected. This is important in controlling public health problems caused by water supply contamination by contact with raw or inadequately treated wastewater.
• CEPT sludge is readily dewatered and processed. The amount of CEPT sludge is generally only 10 to 15% greater than that produced by the removal of suspended solids.

• CEPT is an effective and appropriate first stage treatment process, it may be followed by biological treatment if the incremental effluent improvement, the risk of toxic upsets of the biological process and increased biosolids disposal can be justified and afforded. Subsequent biological treatment plants will be smaller and more efficient because of reduced organic load and increased solubility of the CEPT effluent.

The paper includes a frank discussion of the impediments to the adoption of innovative and appropriate wastewater treatment technologies in the developing world.

While CEPT is already being applied in mega-cities, it is appropriate for small cities as well. Ongoing studies are aimed at reducing the cost and increasing the efficiency of wastewater treatment lagoons frequently used in small cities by combining CEPT and lagoon treatment technologies. CEPT tanks can be used as a pre-lagoon treatment to reduce solids and BOD loading to lagoons or coagulants can be added directly at the lagoon inlet.

Recommendations for needed research are presented.

INTRODUCTION

Population growth in mega-cities and other urban areas of the developing world and the associated water-related pollution and public health problems are a much discussed topic. The important issue is whether the developing world should follow the model of using the municipal wastewater treatment technology of Western Europe and North America or whether there is an alternative "sustainable sanitation" approach?

A committee of the U.S. National Research Council (NRC, 1996) reported on "sustainable water and sanitation services for mega-cities in the developing world." Unfortunately, the report is long on generalities and short on specifics. The authors indicate that "water and sanitation professionals must take a broader view of sanitation to prevent disease resulting from a wide range of activities and multiple exposure routes." On the role of treatment technology, the authors state that "technical innovation should be based on carefully considered performance criteria appropriate to maintaining a healthy environment." The final conclusion notes that, "With appropriate treatment, reclamation and reuse of municipal wastewater for non-potable uses can become an increasingly cost-effective conservation measure."

The issue of appropriate wastewater treatment for the developing world has also been featured in Water Science and Technology (Henze et al, 1997). Half the papers address the definition and analysis of sustainability, while the other half deal with the technology. Most of the technology papers are concerned with non-conventional (and very expensive) collection systems designed to separate, treat and
dispose of liquid and fecal wastes by different processes. An overview paper by Varis and Somlyody (ibid) addresses the issue of global urbanization and asks the question: "Can sustainability be afforded?" They conclude that the conventional urban wastewater infrastructure of the industrialized world is neither sustainable nor transferable. However, they provide no specific answers as to what is affordable or what should be done to solve the water and sanitation problems of mega-cities.

In another exchange by three academic experts in Water Quality International, Keinath (1996) "believes the time has come to seriously consider the direct and deliberate reuse of water for potable uses in the mega-cities of the world." He contends that "treating water to high levels of quality -- is likely to be less costly than further exploiting distant surface and subsurface waters" and recommends focusing research on the further development of advanced oxidation and adsorption processes and membrane technologies. Okun (1996) agrees with Keinath's basic premise, but contends that reuse should be limited to non-potable uses such as agricultural irrigation because this would require only "secondary treatment followed by filtration and chlorination" and thus require no new technology. Alaerts (1997) offers a third perspective, stating that it would be "more cost effective to reduce water demand in factories and in households. Rather than cleaning up a given effluent, we may prefer to promote cleaner production technologies, stimulate in-plant reuse, relocate the plant to less sensitive watersheds, or abolish the industry altogether." He concludes that "innovative and cost-effective technologies are essential components in these schemes." However, he does not identify what these technologies are, nor does he explore the likelihood that developing countries will abolish industries because of environmental concerns.

This paper, prompted by disappointment with the lack of realistic and concrete proposals offered by European and North American water experts, puts forward specific technological proposals in order to encourage the continued vital discussion of which treatment technologies are appropriate for solving the urban sanitation problems of the developing world.

While it is true that some cities (Jakarta, for example) lack a sewage collection system, many urban areas have extensive sewerage systems that discharge untreated wastewater and contaminate adjacent rivers, shallow embayments or coastal waters. Only a small fraction of collected wastewater is treated, usually in "token" secondary plants with conventional primary settling and activated sludge. Such plants frequently suffer from poor performance due to inadequate funds for maintenance and operator training or to biological upsets caused by toxic industrial inputs.

Rather than attempting to prescribe an ultimate effluent end use and its corresponding level of advanced treatment (as in the perspectives of Keinath, Okun and others), it seems much more useful to try to define the most efficient and cost-effective, minimum level of treatment needed to protect public health. Consider Mexico City as an example.
MEXICO CITY -- A CASE STUDY IN MEGA-CITY NEEDS

The Valley of Mexico, with 21 million inhabitants, covers an area of 1300 km$^2$. The city lies on an old lake bed on a high plateau with no natural drainage or source of fresh water. It would appear to be a prime candidate for reusing sewage for potable water since most of the drinking water is pumped from deep ground water wells or from distant lower surface water sources. The city produces an average of 75 m$^3$/s of wastewater and this raw sewage is used to irrigate 85000 ha of agricultural land in the neighboring state of Hidalgo. These crops feed and provide income for the local population. The raw sewage is high in organic, nitrogen and phosphorus nutrients, as well as in fecal coliforms and helminth eggs, a debilitating parasite, in concentrations as high as 250 eggs/L. Because the soil in the valley is poor, the organic material, nitrogen and phosphorus in the wastewater has greatly improved crop yields -- corn production has increased 150%, onion 100%, tomato 94%, etc. (Landa, H., et. al., 1997). The irrigated area receives over 80 kg/ha of nitrogen per year.

Keinath's proposal for reuse of sewage as potable water for Mexico City is mind-boggling when one considers the cost of high-tech tertiary treatment for all or even a significant fraction of the 75 m$^3$/s of raw sewage. The critical issue in Mexico City's use of raw sewage for irrigation is the high prevalence of enteric and parasitic disease among the more than 100,000 agricultural workers in the irrigated areas (CNA, 1995). Mexico City's pressing need is to find a level of treatment that will protect the workers through helminth egg removal and pathogen inactivation, while allowing continued use of the organics and nutrients for irrigation. Okun advocates reuse of sewage for agriculture, but immediately couples it with the need for secondary treatment prior to disinfection. This is consistent with the thinking of most Western environmental planners and engineers. However, it must be questioned whether the capital and operating costs for full secondary treatment of the wastewater of Mexico City, given its other infrastructure needs, is a necessary or feasible option.

During visits to Mexico City in 1993-1995, the authors urged the National Water Authority to consider and test chemically enhanced primary treatment (CEPT), as a single-stage treatment process that would result in a high level of suspended solids removal, including helminth eggs, and would thereby produce an effluent that could be effectively and economically disinfected. This proposal became the basis for a number of pilot and full-scale tests in Mexico City (Murcott, et. al., 1996). Additional pilot plant studies on the use of CEPT alone and in combination with high-rate sand filters have been completed (Landa, H. et.al., 1997).

CEPT is very effective in removing helminth eggs to a range of 2 – 5 eggs/L. Polishing sand filters were added to insure an effluent with less than 1 egg/L. The Mexican authorities made a cost evaluation of CEPT treatment in comparison with conventional primary plus activated sludge treatment for a number of proposed plants (CNA, 1995). For example, for the proposed El Salto plant (15 m$^3$/s treatment capacity and 5.2 m$^3$/s mean flow) the construction cost (including sludge disposal) of the CEPT plant was estimated at US$70 million while the conventional
primary plus activated sludge facility cost was higher by a factor of 1.85. Annual operating costs were US$4 million for CEPT and US$7 million for the primary plus secondary plant. The annual cost of the CEPT chemicals is more than offset by the high energy cost for secondary aeration tanks.

SOUTHERN CALIFORNIA -- A CASE STUDY IN RETROFITTING CHEMICALLY ENHANCED PRIMARY TREATMENT

In 1985, the passage of California’s ocean protection plan required that all treatment plants with ocean outfalls had to achieve suspended solids removal of 75% or greater. At this time, the four largest Southern California plants all had conventional primary treatment; three, the City and County of Los Angeles and Orange County, had partial secondary treatment while San Diego had only primary treatment. Because of rapid population growth, the plants were over-loaded by a factor of two or more above their original design capacity. Plant operators, faced with poor performance due to overloaded conditions, met the State effluent requirement by turning to a century-old potable water treatment process -- the addition of trivalent metal salts, to increase solids removal by coagulation and flocculation. They retrofitted their plants for CEPT treatment quickly and at very low cost.

Physical-chemical treatment of wastewater was a well-known technology that had fallen into disfavor in the second half of the 1900’s because lime, the preferred chemical at high doses, produced very large quantities of additional sludge. The new twist in California in 1985 was the combination of a low dose of ferric chloride (~25 mg/L) as a primary coagulant together with a minuscule amount of an anionic polymer (~ 0.2 mg/L) as a flocculant. The CEPT process improved treatment efficiency considerably with only a marginal increase in primary sludge production over that due to increased solids removal.

At Pt. Loma, San Diego’s overloaded conventional primary plant, suspended solids removal increased to about 85% after the CEPT retrofit. BOD removal increased to more than 55% and phosphorus removal (by precipitation as ferric phosphate) to 85%. Even more impressive was the fact that the increased CEPT pollutant removal efficiencies were obtained at average surface overflow rates of up to 4.5 m/h, about three times larger than commonly used in the design of conventional primary settling tanks. (Morrissey and Harleman, 1992).

San Diego occupies a unique place in the history of urban wastewater treatment in the USA. In the late 1980’s, the City was under intense pressure and a federal court order to comply with the EPA requirement to add an expensive secondary treatment plant. Certain city officials questioned the value of spending two billion dollars to obtain a small increase in BOD removal for an already clean CEPT effluent that was being discharged through a long ocean outfall. Their arguments were: (1) extensive monitoring had shown no degradation of the ocean following the 1985 CEPT upgrade, and (2) since San Diego is at the short-end of California’s fresh water allocation, it would be more sensible and much less costly to construct a new tertiary plant to treat a fraction of San Diego’s wastewater for reuse. Scripps scientists, who had been monitoring the CEPT effluent, strongly supported this viewpoint and San Diego joined with Boston and others in requesting a National
Academy of Engineering review of wastewater management in coastal urban areas. The study was completed (NRC, 1993) and Congress subsequently passed a special secondary treatment waiver for San Diego allowing it to continue CEPT treatment at Point Loma and to build a new water reclamation plant to treat about 15% of its wastewater for reuse on land.

Other plants, such as the City of Los Angeles' Hyperion facility, that had partial secondary treatment, were able to double their secondary flow capacity after CEPT implementation. This was related to the decreased BOD loading to the secondary stage and the fact that the BOD remaining in the CEPT effluent was largely soluble and readily oxidizable.

The first use of low dose chemically enhanced primary treatment in North America was in several Canadian primary plants. These facilities started using CEPT in the early 1980's (Heinke, G. et.al., 1980) in order to reduce the discharge of phosphorus into the Great Lakes. In Europe, a similar process is known as "direct precipitation." For example, in Norway, higher doses (100 - 250 mg/L) of metal salt coagulant are used to meet the requirement for 95% phosphorus removal, with no biological treatment. More recently, chemical treatment with lamella plates has been promoted in France and French Canada at very high overflow rates. In these plants CEPT is followed by aerated biofilters with sludge removal by periodic backwashing. The result, because of the elimination of secondary clarifiers, is a compact, although expensive, treatment plant that can be located in congested urban areas.

IMPEDEMENTS TO CEPT IN THE DEVELOPING WORLD

It is reasonable to ask why, if CEPT is such an efficient and cost-effective treatment technology, is it not more widely known and used. There are several reasons: (1) The California CEPT upgrades were carried out by plant operators who provided no exposure of their results in the technical literature; (2) There are few "basic research" papers on CEPT because the process cannot be studied generically in university laboratories. Bench-scale and pilot plant tests must be done at the site to determine effective coagulant chemicals and dosages. (3) There is a widespread belief that chemical treatment produces "too much sludge." The fact is that low dose CEPT produces only 10 to 15% more sludge than that resulting from the removal of suspended solids. (4) Private engineering design firms are reluctant to use what they consider to be new approaches. A recent study by the American Consulting Engineers Council reported that three-fourths of their respondents avoid using innovative technology because they are afraid they could be sued if something goes wrong. This is a common "red herring" used to justify the continuation of past practice. (5) There is greater profit in designing plant expansions than in retrofitting and upgrading existing plants with CEPT. (6) The practice in the USA is for a municipality to engage a firm on a non-competitive basis to design a plant, ask bids for construction and then operate the plant with city employees. This discourages innovation because the only competition is in the construction. In contrast, the European practice of bidding on a design/build/operate package encourages competition through the use of cost-effective innovative treatment processes. European design firms who engage in this type of bidding have their own research
laboratories to insure that they understand and advance the treatment processes they propose.

There are now a growing number of examples of CEPT being tested and implemented in the developing world. Their objective is to protect public health, in a cost-effective manner, by first building the minimum level of wastewater treatment that permits effective removal of pollutants and deactivation of pathogens. Because of the increased surface overflow rate compared to conventional primary treatment, CEPT provides the minimum cost per unit volume of wastewater treated. There is no constraint on future biological upgrades; in fact, CEPT technology insures that any subsequent biological treatment, if it can be justified, will be more efficient and smaller in both size and cost.

CEPT EXPERIENCE IN HONG KONG

In 1994 the British government of Hong Kong appointed an International Review Panel (including the first author) to resolve a conflict over plans for the collection and treatment of sewage from the most populated areas of Kowloon and Hong Kong Island. The long range government plan called for a conventional primary treatment plant within the harbor at Stonecutters Island (SCI) and effluent discharge through a long (20+ km) ocean outfall into southern waters. The mainland government complained that the treatment was inadequate and that pollution would be exported from the harbor to Chinese territorial waters.

The Panel completed its review in 1995, recommended that (1) the initial treatment at SCI be upgraded to CEPT, (2) a pilot plant study of the CEPT process and (3) the long outfall be postponed. Subsequently the government redesigned the conventional primary as a CEPT plant and in doing so reduced the number of settling tanks to two-thirds by taking advantage of a higher surface overflow rate. (Harleman, Harremoes & Qian, 1997)

In May 1997, Hong Kong completed construction of the world's largest CEPT plant having a maximum capacity of 40 m³/s and a 20 m³/s average flow. Operating data from the CEPT plant show removals of the order of 85% for suspended solids and 74% for BOD with a dosage of only 10 mg/L of ferric chloride. The surface overflow rate of about 60 m/d is roughly twice that for conventional primary treatment. The use of seawater for flushing toilets undoubtedly contributes to the remarkable efficiency of the Hong Kong CEPT plant.

In April 2000 the Hong Kong government appointed a new International Review Panel (again including the first author) to address the issue of completing the collection and treatment of all of Hong Kong Island’s sewage and meeting ammonia water quality standards. The Government plan again proposed construction of the long southern outfall in order to achieve ammonia objectives by multi-port diffuser dilution. In November 2000, the Panel submitted its report (IRP 2000) and recommended elimination of the long outfall, by-passing secondary treatment and going directly to nitrification of the CEPT effluent at SCI using compact biological aerated filters. Discharge of the tertiary effluent will meet water quality standards at the local SCI outfall. The Government, in its initial response (EPD Hong Kong
2001) decided to move ahead with the EPD recommendations. In the view of the IRP this may ultimately result in a saving of the order of one billion US dollars.

CEPT EXPERIENCE IN BRAZIL

Bench-scale and full-plant CEPT demonstration tests have been successfully completed, first in Sao Paulo, under the sponsorship of the state wastewater agency. (SABESP, 1996) Next, in Rio de Janeiro, in 1997, the World Bank requested a demonstration of CEPT technology at an existing treatment plant. The objective was to show whether CEPT technology should be used in future treatment plants designed to solve severe eutrophication problems within Guanabara Bay. One of the major treatment objectives is low-cost phosphorus removal, the limiting nutrient controlling the large algal blooms that cause oxygen depletion and odors in the Bay. Tests of CEPT showed that it is possible to remove about 90% of the phosphate as well as high levels of TSS and BOD. (Harleman and Murcott, 1998) The first two CEPT treatment plants in Rio have been constructed by CEDAE, the state agency, and have begun operation.

In 1998 it was decided to use the Brazil CEPT experience to provide Master of Engineering thesis opportunities for Massachusetts Institute of Technology students. Site visits to design, test and collect data on innovative treatment processes were made. The focus was on municipalities which have overloaded and poorly functioning plants. In Brazil, most wastewater treatment in medium size cities is by open lagoons at the edge of the urban area. The usual method of upgrading existing lagoon performance and treatment capacity is by cleaning and reconstructing the lagoons and installing surface aeration units. However, in addition to the initial costs, most cities cannot afford the large annual costs to run and maintain the aerators.

Students obtained data on anaerobic and facultative lagoons serving a coastal community having a large variation in seasonal population. A numerical model (Ferrara and Harleman, 1980) was used to predict the performance of the wastewater treatment lagoons. The calibrated model was then used to design two treatment upgrade alternatives for a city which had planned to upgrade existing lagoons by installing aerators. (Chagnon, 1999)

In the first treatment upgrade alternative, a small CEPT tank is placed in front of the first lagoon. This reduces the solids and BOD load on the lagoons and eliminates the need for aerators. The second alternative used an in-lagoon CEPT concept whereby chemical coagulants are added directly at the inlet of the first lagoon, again eliminating aerators. This type of CEPT lagoon, first successfully used in Scandinavia (Hanaeus, 1991), would be expected to perform better in the warmer climate of Brazil. A comparative cost study showed that both alternatives were less expensive, in capital and O & M costs, than the original aerated lagoon design. (Cabral, et al, 2000)
CONCLUSIONS AND RECOMMENDATIONS

Public health is the major water-related environmental concern in urban areas of the developing world. In many instances, drinking water and receiving water sources are contaminated by raw or inadequately treated wastewater effluents. Even when conventional primary treatment exists, its effluent cannot be effectively disinfected.

The objective of initial wastewater treatment investments or upgrades of existing treatment facilities should be a high-flow rate, low-cost treatment technology such as CEPT, that provides a high level of suspended solids removal, thereby permitting effective pathogen inactivation by disinfection.

The issue is not one of chemical versus biological treatment. Chemically enhanced primary treatment is the most cost-effective first step, it can always be followed at a later stage by more advanced biological treatment processes if they can be justified and afforded.

Most CEPT studies in developing countries have been carried out on a short-term ad-hoc basis with little time and effort devoted to exploration and research. There is a clear need to develop long-range research and field studies at several existing treatment plants having different raw waste characteristics.

The following topics are recommended for further research:

• The interaction of metal salts as coagulants and anionic polymers as flocculants. This would explore the optimization of combinations of metal salts and polymer dosages for maximum removal efficiency at high surface overflow rates;

• The trade-off between various proportions of metal salts and cationic polymers as primary coagulants. This would offer potential savings in sludge production which might offset the higher cost of the polymers;

• The efficiency improvements in CEPT technology through controlled mixing of coagulants and flocculants. This would demonstrate the effectiveness of mixing and flocculation devices upstream of settling tanks;

• The effectiveness of recycling waste potable water treatment sludge and/or CEPT sludge. There is evidence that either may be effective in reducing coagulant doses;

• The efficiency of combining CEPT, with primary effluent filtration or CEPT with aerated biofilters. The latter effectively uses the highly soluble BOD remaining after CEPT and, by backwashing, eliminates the cost and space required by secondary clarifiers.

• The cost and energy savings of CEPT versus activated sludge wastewater treatment plants.
• The interaction of CEPT and wastewater lagoons with either pre-lagoon CEPT treatment or in-lagoon chemical treatment. Collection of data on operating CEPT/lagoon combinations to improve numerical modeling of lagoons to optimize final effluent quality and ultimate sludge disposal.

• The potential uses of processed CEPT sludge for agricultural applications. Collection of data on effectiveness of nutrients in the sludge.

• The disinfection by UV, or other options, following CEPT treatment.

REFERENCES


EPD Hong Kong 2001 A Clean Harbor for Hong Kong, March 2001 See website: www.info.gov.hk/ssds.review


