PN-ACD-232

Anaerobic Enhanced Treatment of Wastewater and Options for Further Treatment

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The vast majority of the world's population and businesses does not have access to, or utilize any wastewater treatment technology This lack of treatment places an enormous burden on natural systems but can represent an opportunity for USAID, and others to positively impact the economic development, human health, and environment of the communities that do not currently have access to treatment

Due to the high capital and operation costs generally associated with traditional aerobic technologies, wastewater treatment is typically not provided, even where wastewater collection systems are in place The environment in and down stream from many cities around the world can no longer absorb our wastewater, nature has been overburdened This report, with a focus on *low cost, low maintenance anaerobic reactors,* is a positive step in identifying alternative technologies that are three to six times less expensive than traditional technologies

Anaerobic treatment of wastewater has been a viable technology used around the world for centuries Better understanding of both the engineering and the biology involved in these natural enhanced processes has led to technological advances that have made anaerobic *reactors* a viable treatment technology These systems are modular, compact, low cost, effective and are operating in many countries It is a technology on the verge of commercialization With assistance from the international donors, it will spread quickly, as developing countries explore less costly, yet effective technologies to deal with their wastewater issues

It is our hope that this report provides affordable and effective options for both the engineers and policy makers around the world as they consider the treatment alternatives available to them

Eric A Peterson, PE
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Capital Projects and Engineering
Center for Environment

Acknowledgements

The authors would like to express appreciation to the following persons and organizations for their contributions to the preparation of this document

Eric Peterson, Dwight Walker, AID and Felipe Mantaiga, USAID/India

Steven V Allison, AQUACONSULT, Ltd

Professors Alvaro Orozco and Eugenio Giraldo Gomez, University of the Andes, Bogota

Ing Jenny Rodriguez and Ing Ulises Rincon Ramirez, CDMB (Corporacion Autonima Regional para la Defensa de la Meseta de Bucaramanga)

DHV Consulting Engineers, Mr Aris Shellinkhout

Haskoning Royal Dutch Consulting Engineers, Johan Schaapman, Wim Wiegand, V N Sontakke

IRAM Consult, Messrs Abdullah and Parvez Khan

Jal Nigam, Government of Uttar Pradesh, India

Water and Environment Foundation (WEF)

Asian Institute of Technology, Prof Chongrak Polprasaert

The World Bank, Andrew Macoun

1. Anaerobic Enhanced Primary Treatment of Wastewater and Options for Post-Treatment

Exploding industrialization and urbanization in developing countries are polluting groundwater and degrading the quality of surface waters by overloading them with more organic material than can be assimilated naturally Raw or insufficiently treated wastewater spreads pathogenic microorganisms and intestinal parasites in the environment and ultimately to humans

Improved water supply and sanitation service levels are needed in developing countries, but the high cost of the infrastructure, scarcity of development funds and difficulties in *managing* the relatively few facilities that exist are major constraints

Conventional mechanical treatment facilities in developing countries have had a sparse record of success They frequently do not function as expected because of a variety of technical, financial and institutional reasons Alternative treatment technologies emphasize cost reduction, integrated system management, minimal mechanical operations, water reclamation and nutrient conversion wherever feasible The technologies described in this report include simplified, lower cost wastewater collection infrastructure, anaerobic enhanced primary treatment and lagoon-based post-treatment processes that can achieve high effluent quality levels and that can be managed adequately by non-specialists

Mechanically aerated wastewater treatment systems are more compact than naturally aerated systems and are capable of providing an effluent low in BOD_5 (<10 mg/l) Conventional treatment systems are used in large, medium and small scale applications for domestic and municipal wastewater effluents Conventional treatment systems that have been used in developing countries include the *activated sludge* process and more recent variants, including *sequencing batch reactors, extended aeration* and the *oxidation ditch*

The disadvantages of conventional treatment that are most prominent in developing countries include high power consumption, vulnerability to power outages, high maintenance requirements and the need for close supervision by skilled operators

ANAEROBIC REACTORS

Anaerobic treatment not only removes solids, but includes active biological *stabilization* of the majority of oxygen consuming substances Anaerobic treatment processes can achieve an effluent quality *intermediate* between the primary and secondary that can be classified as an *enhanced* primary treated effluent Anaerobic treatment removes the major part of the carbonaceous oxygen demand from raw wastewater, but typically the residual *nitrogenous oxygen demand* in the effluent requires further treatment to be competitive with a conventional secondary treatment process

The upflow anaerobic sludge blanket (UASB) reactor is a high rate, suspended growth type of reactor that is becoming popular for municipal and industrial wastewater treatment in many developing countries Annex 2 provides design parameters developed for UASB reactors

Organic loadings of up to 15 kg COD/m^3 can be applied to the UASB reactor for most types of wastewater effluents Depending on the composition of the wastewater, the removal efficiency of the UASB process may vary between 60-70 percent for COD and 75-85 percent for BOD_5, at influent temperatures between 20-35° C

The UASB reactor traps particles of organic material in a "sludge blanket" and digests them over a long time period, while passing the liquid fraction through in a matter of a few hours As a result, the volume of the reactor is kept to a minimum and the treatment plant is compact The UASB reactor is designed around two main criteria *hydraulic retention time*, the average amount of time that the liquid part of the wastewater stays in the reactor, and *solids retention time*, the average residence time of the solids in the reactor A properly designed UASB reactor eliminates the need for mechanical mixing and has few moving parts Typically, a UASB treatment plant may need pumps only to remove excess sludge from the reactor

The authors visited four full scale anaerobic treatment plants in India and Colombia that were commissioned in the early 1990s Capital and operat-

ing costs for municipal wastewater treatment range from $5/caput and $0 03/caput respectively in India, to $13 9/caput and $0 43/caput respectively in Colombia Details about the design, effectiveness and costs for these treatment plants are provided in Annex 3

ADVANTAGES AND LIMITATIONS OF TREATMENT WITH ANAEROBIC REACTORS

Anaerobic treatment of wastewater is an effective *enhanced primary* treatment option for developing countries, particularly those with mild climates, and has important advantages over aerobic processes

- Easier to manage with relatively less skilled employees than conventional treatment plants,
- Costs on the order of 3-6 less than aerobic secondary treatment plants,
- Few moving parts, lower operating costs, little or no power consumption,
- High strength waste streams can be treated efficiently at no energy penalty,
- Shock loads handled better than aerobic systems,
- Large flow variations and prolonged shutdown are not problematic,
- Reduced inorganic nutrients in effluent are ideal for plant uptake,
- Low amounts of residual sludge byproduct, sludge has good settling properties, is easily dewatered and needs no additional treatment,
- Biogas fuel may be economical to utilize for large scale facilities,
- Can attenuate or degrade many refractory organic compounds,
- Virtually complete stabilization of organic material to CO_2 and methane

LIMITATIONS OR DISADVANTAGES

- Best reactor temperature is 20° C and above, lower temperatures slow reaction rate,
- Longer reactor startup time because of slow growth rate of anaerobic bacteria,
- Additional treatment is typically required to meet secondary quality standards,
- Odor control measures are more important than for aerobic treatment,
- Toxic effects of high concentrations of heavy metals, toxic organics, free ammonia (> 50 mg/l) and free H_2S (> 250 mg/l) may inhibit methanogenic activity,
- Chemical buffering may be required to maintain alkalinity in reactor,
- Corrosion resistant materials, such as plastics and masonry coatings are required for the reactor vessel and pipes

POST-TREATMENT

Mechanical Aeration Where skilled manpower and a reliable electric power supply are available, but not enough affordable land for pond systems, the investment and operating costs of conventional mechanically aerated treatment plants may be reduced by using anaerobic reactors as the initial major treatment process Research in Brazil demonstrated that using an anaerobic reactor in series with a mechanically aerated post-treatment process has several important advantages

- The volume of the anaerobic/aerobic treatment plant will be about half the volume of a conventional activated sludge plant, reducing the capital cost correspondingly
- The demand for electric power for mechanical aeration is reduced by more than 50 percent, reducing operating costs,
- The anaerobic reactor replaces both the primary clarifier and the sludge digester of a conventional system Excess aerobic sludge can be recirculated to the UASB reactor, where it will be stabilized and densified, facilitating sludge handling,
- Nitrification and denitrification zones can be included to remove nitrogen, and the anaerobic sludge can provide a carbon source to support denitrification

Waste Stabilization Ponds Three basic types of non-mechanical pond-based post primary treatment processes are

- Pond systems designed to favor algae production over aerobic bacteria Such systems can remove nutrients and are capable of effective pathogen destruction,
- Constructed wetlands, where aerobic bacterial films on plant roots provide treatment, and
- Pond systems designed for the cultivation of floating aquatic macrophytes, such as species of the duckweed family The plants remove nutrients from the water and convert them into commercially valuable plant biomass instead of algae

Brazilian researchers have developed design criteria for pond systems that provide effective post-treatment of anaerobic reactor effluents in a warm climate An anaerobic reactor substitutes for the initial cells in a conventional pond series that are designed to stabilize organic material The size of the post-treatment ponds is only 20 percent of the space of a conventional series of 4-5 ponds designed to receive raw wastewater

A plug flow pond system for post-treatment can be designed to maximize algae growth, so that photosynthesis by algae predominates over bacterial growth Light can penetrate almost all of the water column in a shallow pond (0 3-0 65 m depth) because of the relatively low turbidity of the reactor effluent The post-treatment ponds are designed to achieve high pH values (above 10) during the day, resulting in ammonia stripping and phosphate removal by precipitation

Aquatic Farming Systems There has been increasing interest in recent years in using *aquaculture* systems as natural sinks for oxygen consuming substances and wastewater-borne and recognition of their capacity to provide an advanced quality final effluent The common *duckweeds* are group of floating macrophytes with excellent potential as a commercial crop plant because of their high growth rate, high nutritional value and low fiber content The duckweed plants cover the surface of the water in a dense mat that interferes with mosquito breeding, and the quiescent conditions under the mat are ideal for sedimentation of suspended solids

Agronomic management of the duckweed plants on wastewater can result in production rates of about 300-800 metric tons of fresh biomass per hectare per year (ha/year), or the equivalent as a dried meal of about 20-40 metric tons ha/year Dried duckweed meal can substitute for equal quantities of soybean meal in balanced poultry feeds, and fresh duckweed satisfies the nutritional requirements of certain fish grown in ponds, such as tilapia and a carp polyculture

Integration of anaerobic enhanced primary treatment of wastewater and duckweed farming constitutes a *synergistic* processes that is (a) a complete wastewater treatment technology and (b) a farming system that is capable of producing more high quality protein than soybeans on an equivalent land area

Land for a duckweed post-treatment system is similar to a waste stabilization pond series The amount of treatment surface area necessary to achieve an advanced quality treated effluent was about 1 6 m^2/PE (PE = person equivalent) in a pilot project in Bangladesh

The potential revenues to an owner/operator of a treatment and duckweed-fed fish production system in Bangladesh are attractive For example, at an average live weight price of fish of $1 5/kg, the gross revenues from duckweed-fed fish production in Bangladesh is on the order of $2 4-$3 6/PE/year, or about $0 38-$0 56/m^2/year in gross revenues from the total amount of land used for the treatment and production system

Duckweed aquaculture that does not include fish production has dried duckweed meal as the final product The total amount of land needed for duckweed production in Bangladesh is 2 1 m^2/PE If duckweed meal is priced the same as soybean meal, between $0 25-$0 30/kg, gross revenues from duckweed meal sales will be about $0 38-$0 46/m^2/year of total land used, or about $0 80-$0 96/PE/year

LAND ISSUES

Anaerobic reactors for initial treatment, followed by pond, wetland or aquatic farming systems for post-treatment represent a flexible configuration option that can reduce both land and infrastructure costs compared with pond-based systems alone The reactors (or septic tanks) can be located in or near the urban area in one or more locations Because anaerobic reactor effluent is virtually free of settleable solids it can be conveyed to the post-treatment site through a *small diameter effluent drainage* system designed as a *hydraulic* system, rather than as a sewer to convey raw wastewater This type of configuration can have several important advantages

- Reduced treatment and land requirements at the post-treatment facility, because major removal of solids and oxygen consuming substances takes place upstream of the post-treatment facility,
- Reduced construction costs of the effluent collector that replaces the trunk sewer because of shallower, narrower trenches, elimination of manholes and minimum requirements to control the gradient and horizontal alignment of the pipes,
- Reduced materials costs because smaller diameter pipes, running full, can handle the lower peak flows that result from attenuation of peak flows in the reactors, and
- Lower maintenance costs because blockages in the effluent conveyance system are less likely

FINANCIAL AND ECONOMIC ISSUES

Technologies for both wastewater collection and treatment in developing countries should be selected to protect public health and the environment, while ensuring the fullest use of the water resource The selection process should factor in the costs and availability of land, labor, equipment, and building materials and the cost, availability

and reliability of support services, such as utilities, equipment and systems maintenance Technology selection objectives that should apply in most developing countries include

- Technological simplicity,
- minimal capital and operating costs,
- maximum treatment and removal efficiency for capital and recurrent investment, and
- water reclamation and reuse capability to offset costs

COSTS AND COST COMPARISONS

Treatment plant designs have become sufficiently standardized that developing lists of quantities of essential materials and equipment is relatively straightforward Recent similar projects can provide the basis for unit prices Within a particular country some site-specific variations may be expected, but comparisons with several recent projects in that country can provide important information about the economy of a system utilizing an anaerobic reactor More importantly, comparisons of capital and operating costs among alternative designs for a specific new site are essential if sound investment decisions are to be made For example, a comparative study conducted in Colombia in 1992 concluded that the costs of anaerobic treatment plants (including post-treatment to secondary quality) for municipal wastewater appear to be between three to six times less than conventional activated sludge and extended aeration

An analytical framework is presented in Annex 4, using capital and operating costs based on recently constructed plants or recently completed studies The analytical framework might be used to indicate the kinds of data required for a useful evaluation of proposed projects The single-sheet analytical approach presented was designed to facilitate sensitivity testing on uncertain economic values

ECONOMIC AND FINANCIAL ANALYSIS

With appropriate site-specific input, the analytical format presented in Annex 4 will produce estimates of potential economic returns to investment in the construction of wastewater treatment facilities These estimates will be useful primarily to compare the conventional approach with possible alternatives Which method to use to estimate the treatment benefit is not prescribed Experienced engineers and economists working in that country would be able to make the estimates and could suggest where the process of sensitivity testing should start

Besides the basic treatment benefit, there are a variety of productive ways of reusing the treated effluent almost everywhere, but particularly in countries with water scarcity The unit *values added* for each of these uses are amenable to estimation The examples presented in Annex 4 assume that no wastewater is treated to potable quality Instead, an allocation has to be made between on-site use (which in these examples was an aquatic production system for duckweed and fish) and off-site uses, either in industry or irrigation

New financing trends are emerging financing of public works by the private sector on a *build, own, operate* (BOO) or *build, own, operate, transfer* (BOOT) basis Consortia including contractors and bankers build a wide range of facilities The fact that the builders' own funds are used leads to an increased focus on economy of design

Alternative infrastructure that is less costly to operate is increasingly of interest to municipal decision makers, and the possibility of positive cash flows from a treatment is attractive The possibility of corporate profits induces engineers and contractors to seek out bankers Funds for construction come from non-traditional sources, and the attention of all participants is focused on less costly technologies It is here that on-site, productive uses of the wastewater resource, such as duckweed and fish production, are likely to play an important role in the future

Anaerobic-enhanced Primary Treatment of Wastewater and Options for Post-Treatment

I BACKGROUND

1 1 PURPOSE

The purpose of this report is to analyze anaerobic enhanced primary treatment of wastewater and options for further treatment, using examples from developing countries Particular attention is given to the *upflow anaerobic sludge blanket* (UASB) technology because of the successful application of relatively large scale treatment plants in Latin America and South Asia and the increasing acceptance of this technology in developing countries

The review also refers to conventional "secondary" treatment technologies that are common in industrialized countries in the temperate zone Options for further treatment of anaerobically treated effluents are examined, and anaerobic and aerobic treatment systems are compared

Treatment of "point sources" of pollution is considered, e g , treatment of municipal wastewater and effluents from food processing plants An example of anaerobic treatment of an industrial (tannery) effluent diluted with municipal wastewater is cited in a case study Treatment of non-point sources of pollution, such as agricultural runoff is excluded from consideration

1 2 WASTEWATER ISSUES IN DEVELOPING COUNTRIES

According to the World Bank's 1994 Annual Report, "Adequate water supply and sanitary disposal of wastes are fundamental to a reasonable quality of life Poor sanitation and lack of access to safe water contribute to more than two million deaths annually, while large economic and environmental costs are incurred to compensate for poor quality services "

The explosion of industrialization and urban growth worldwide is polluting groundwater and degrading the quality of surface waters by overloading them with more wastewater-borne organic material than can be assimilated naturally For example 45 percent of all streams in peninsular Malaysia are considered effectively "dead" from the effects of eutrophication, and the typically short rivers transport pollutants rapidly to coastal waters (Ref 1)

There is great demand for improved water supply and sanitation service levels in many developing countries, but the high cost of the infrastructure and competition for development funds from other development sectors are major constraints Furthermore, while most urban populations are willing to pay for wastewater collection, there is general resistance to bearing the costs of treatment In most developing countries the cities that have wastewater collection usually do not treat the effluent For example, WHO reported in 1987 that only about 10 percent of those in Latin America have treatment

There are significant differences between the industrialized, affluent countries and most developing countries that shape the discussion about choice of wastewater treatment technologies differences in climate, hydrology, availability of capital, the cost of labor, skill levels and access to reasonably priced energy and large variations in the capacity of the environment to assimilate wastes

The key issues that constrain wastewater treatment in most developing countries are difficulties in managing the relatively few facilities that exist, followed closely in importance by the high cost of building conventional treatment facilities Concessionary financing is often available to build treatment plants, but not to support operating costs Recurrent costs are almost always regarded as the responsibility of the owners, usually the local government From the point of view of the local government technologies that are inexpensive to operate and manageable by non-specialists are preferable to those that will strain their budget and management resources

The two primary historical justifications of wastewater treatment have been (a) to prevent the spread of organisms that cause infectious diseases in humans, and (b) to remove biodegradable organic material that pollutes groundwater and upsets the ecological balance in surface waters A third reason, particularly important in water scarce regions, is to be able to reuse the treated effluent

directly and safely for economically productive purposes

1 21 HEALTH ISSUES

Enteric diseases are the leading cause of mortality and morbidity among children in developing countries Raw or insufficiently treated wastewater is a vehicle for spreading pathogenic microorganisms and intestinal parasites in the environment and ultimately to humans Water scarcity in many countries has led to irrigation of vegetable and other crops with untreated wastewater and consequent exposure of the public to serious health risks (Ref 2)

1 22 EFFLUENT DISCHARGE GUIDELINES IN DEVELOPING COUNTRIES

In general establishing adequate effluent discharge guidelines has not been a high priority in developing countries Where they exist, enforcement has been constrained either by inadequate regulatory budgets or political considerations The higher profile of environmental issues worldwide appears to have provoked a wave of environmental legislation, for example in Costa Rica, Chile, Colombia and Argentina

1 23 ENVIRONMENTAL POLLUTION

Untreated or inadequately treated wastewater discharged into a receiving stream brings with it biodegradable organic material that diverse communities of microbes decompose These reduction/oxidation processes consume dissolved oxygen in streams and *mineralize* organically bound nutrients that then become available to plants The mineralized nutrients stimulate growth of algae at the base of the food web Excessive microbial depletion of dissolved oxygen, or *eutrophication,* can result in the inability of streams, lakes or coastal waters to support aerobic forms of aquatic organisms

Municipal wastewater effluents in many developing countries tend to be more concentrated than in industrialized countries because less water is used on average in household activities Where the climate is seasonally dry or arid, the small amount of surface water restricts the capacity of the environment to dilute and assimilate wastewater-borne pollutants In such cases the economic value of good quality water is highest, and the hazard of wastewater-borne pollution of surface and groundwater resources is magnified compared with regions with more rainfall Adequate wastewater treatment protects the quality of the water resource by intercepting and fixing wastewater-borne pollutants while restoring wastewater quality to a level suitable for reuse

1 24 RESOURCE RECOVERY

A systems approach to water resource management recognizes that wastewater management is simply another component of water resource management, with an associated set of costs and benefits and definable linkages to the rest of the hydrological system The most important linkages are the *amount* and *quality* of water needed by the city and the effects of wastewater effluents on the quality of rest of the water resource

Figure 1 shows that the amount of water available per person has been declining throughout the world as a result of expanding populations and environmental changes (Ref 3) Water scarcity has resulted in a series of problems degradation and overuse of water resources and increasing competition and conflicts among user groups that are provoking policy makers to reconsider wastewater disposal practices

Worldwide, agriculture accounts for about 69 percent of water use, industry 23 percent and domestic consumption about eight percent Water use patterns, however, vary from country to country and within single countries Water demand for irrigated agriculture is particularly high in arid regions, such as the Middle East and North Africa, and there is increasing demand to satisfy urban needs (Ref 4)

Traditionally, urban water supply has followed a *flow through* model, importing high quality water and discharging low quality *used* water into the public domain, often to the detriment of the interests of downstream users, who typically bear the costs of environmental pollution A more rational economic model would provide for reuse of a large fraction of the wastewater resource within the urban area while discharging insignificant amounts of pollutants into the general environment

Where the development of additional supplies of high quality domestic water is very costly, wastewater is likely to be an economical source Treated wastewater effluents can substitute for high quality water in applications that can accept a lower level of chemical and biological quality, such as irrigation of crops and parklands, flushing toilets and many industrial applications Although an unconventional source, wastewater has characteristics that can be advantageous in an urban setting

- it is a *renewable* resource whose availability mirrors water consumption, and

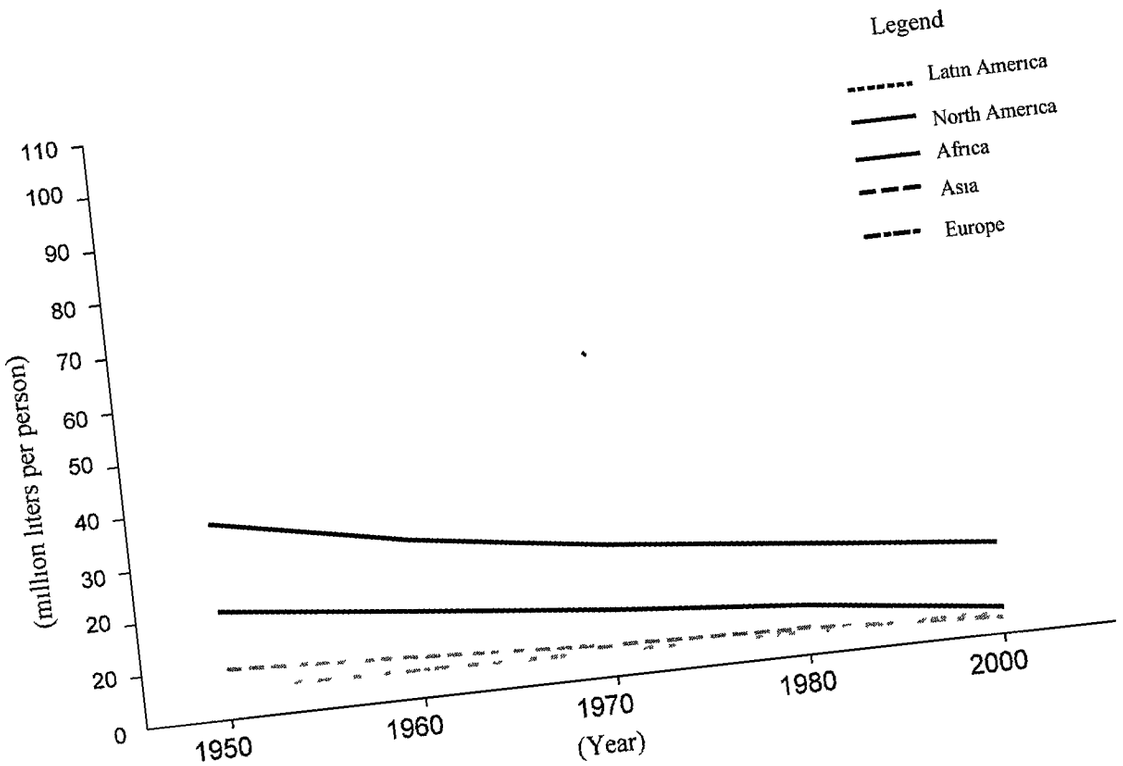


Figure 1
Water Availability per Person by Region From 1950 2000

- it is located near the areas where it is needed, minimizing transport costs

Reuse of treated wastewater effluents conserves water resources by reducing the net amount of water extracted from the primary source In addition to providing health benefits planned reuse of treated wastewater can result in several economically important benefits, including

- the value of the reclaimed water, equivalent to the opportunity cost of developing an alternative supply,
- the value of the water and nutrients to a crop production system,
- the value of avoiding or mitigating environmental damage to receiving water bodies

1 25 SUSTAINABILITY OF WASTEWATER TREATMENT FACILITIES

Where conventional mechanical treatment facilities exist in developing countries, they frequently do not function as expected for many of the following reasons

- shortage of operating capital,
- unreliable or expensive electric power supplies,
- insufficient numbers of trained technical personnel,
- inadequate or unreliable resupply of spare parts,
- public sector institutional problems

Alternative treatment technologies developed over the past 20 years emphasize cost reduction, integrated system management, minimal mechanical operations, simple infrastructure, water reclamation and nutrient conversion wherever feasible Technologies include simplified, lower cost wastewater collection infrastructure, anaerobic enhanced primary treatment and lagoon-based post-treatment processes that can achieve high effluent quality levels and that can be managed adequately by non-specialists

Two basic types of non-mechanical lagoon-based post primary treatment processes are

- Pond systems designed to favor algae production over aerobic bacteria Such systems can remove nutrients and are capable of effective pathogen destruction, and
- Biological conversion of nutrients into useful plant biomass instead of algae, for example, floating aquatic macrophytes of the duckweed family

These integrated systems have many characteristics that suit the needs of developing countries relatively low construction and operating costs, negligible energy requirements, few moving parts, construction with locally available materials and management that can be supplied (after appropriate training) by semi-skilled personnel and farmers

Wastewater treatment systems that are organized as *production systems* yield direct benefits in the form of fungible products, such as reusable water, animal feedstuff and food If fees for the service of wastewater treatment are collected, they add to the potential revenue stream from the treatment and farming systems The owners of a profitable system have a clear vested interest in maintaining it in good working order Integrated treatment and production systems managed as a business are inherently more likely to be sustainable than a traditional, public sector approach to treatment, where the benefits are more diffuse, longer term and not directly related to the welfare of the owners and operators of the system

1 3 WASTEWATER TREATMENT

"Treatment" of municipal wastewater depends on natural processes, such as gravity to clarify an effluent and bacterial action to stabilize the biodegradable organic fraction Pathogenic organisms are removed through natural die-off, deprivation of appropriate hosts and competition from other organisms in a generally hostile environment Adequate detention time and temperature are the two most important variables affecting pathogen mortality (Ref 5)

Basic treatment mechanisms include screening, sedimentation and filtration to remove solid material, stabilization of biodegradable organic material by bacterial degradation and removal of inorganic nutrients, such as nitrogen and phosphorus, by several mechanisms, including bacterial nitrification and denitrification, bioaccumulation by plants, adsorption or chemical precipitation

Complete wastewater treatment consists of a series of steps, commonly defined as follows (Ref 6)

- *Preliminary* treatment, removes large and heavy solids by screening and degritting,
- *Primary* treatment sedimentation of 45-70 percent of settlable solids that contain significant amounts of oxygen consuming substances (20-40 percent), but little or no removal of colloidal and dissolved organic matter,
- *Secondary* treatment consists of removal of about 85 percent of suspended solids and BOD_5 /COD and partial stabilization of the latter and some destruction of pathogenic organisms,
- *Advanced,* or *tertiary* treatment is an added stage of biological, chemical and physical processes to treat wastewater beyond the secondary stage Removal of up to 99 percent of residual suspended solids and nutrients, the most important of which are nitrogen (N) and phosphorus (P)

The nomenclature of the successive stages of treatment, *primary, secondary* and *advanced,* reflects the quality of the effluent at particular points on a continuum that ends with an effluent similar to potable quality water Most technological approaches, conventional or innovative, arrive at or pass through the primary stage, during which the majority of the solid material is removed along with a significant portion of the oxygen consuming substances associated with those solids

Anaerobic processes are capable of achieving an effluent quality *intermediate* between the primary and secondary categories Anaerobic treatment, in addition to the passive process of solids removal, includes active biological *stabilization* of the majority of oxygen consuming substances through microbial degradation of organic particulate matter and colloidal and dissolved organics The result of thorough anaerobic treatment is an effluent that may be classified as an "enhanced" primary treated effluent

Complete treatment, or treatment to the advanced stage, is typically not undertaken except to protect economically important receiving bodies of water against eutrophication, or to meet specific criteria for a particular reuse application The main reason is the high cost infrastructure and operating costs escalate dramatically to achieve an advanced quality final treated effluent In addition, operators with specialist knowledge are needed to manage the historically prevalent treatment processes

1 31 TYPES OF WASTEWATER EFFLUENTS

Table 1 characterizes typical municipal wastewater as "weak", "medium" and "strong" in terms of the concentrations of the major constituents, oxygen consuming substances (BOD_5), suspended solids (TSS) and nutrients (N and P) Generally, the stronger the effluent, the greater the investment in infrastructure and energy inputs required to

Table 1
Characteristics of Raw Municipal Wastewater

Parameter	Weak	Medium	Strong
BOD_5 (mg/l)	110	220	400
TSS (mg/l)	100	200	350
N_{total} (mg/l)	20	40	85
P (mg/l)	4	8	15
Fecal coliforms (most probable number per 100 ml)	10^8	10^8	10^8

Source Metcalf and Eddy 1984

achieve an acceptable quality of treatment Also shown is the typical concentration of fecal coliforms, a group of bacteria that inhabits the human digestive system These bacteria are indicator organisms used to evaluate the biological quality of a wastewater effluent in terms of its potential to contain viable pathogenic bacteria

1 4 TREATMENT SYSTEMS CURRENTLY IN USE IN DEVELOPING COUNTRIES

1 41 "PASSIVE" OR "NATURAL" SYSTEMS

Waste stabilization ponds are the most common wastewater treatment technology used in developing countries In terms of numbers of facilities pond systems outnumber all others in the United States and Canada They may be used in conjunction with other treatment technologies, or alone When used alone, they are usually designed as a series of three to five cells that hold the wastewater for at least 20-25 days to provide for adequate pathogen removal (Ref 7)

Waste stabilization ponds have been widely utilized in communities where land is available at affordable prices Construction costs are low and pond systems are not difficult to operate and maintain compared with mechanized facilities However, they are land intensive and the effluent often contains large quantities of suspended solids, mostly algae, that transmit organic pollution to receiving water bodies

The first pond in a typical series, the primary pond, receives raw wastewater and functions as a sedimentation basin with a 2-5 day retention time An anaerobic primary pond may be 2 5-5 m deep It is a low rate anaerobic reactor, removing 90-98 percent of the easily settlable solids and 30-60 percent of influent BOD_5 The remaining ponds in the series are sites for sedimentation of suspended solids and removal of residual BOD_5 by the action of heterotrophic bacteria

Pond systems are more effective than most conventional wastewater treatment processes at pathogen destruction Pond systems can remove 99 99 to 99 999 percent of pathogenic bacteria, viruses and intestinal parasite eggs, so that the treated effluent is *biologically* safe for agricultural reuse, e g , safe for agricultural workers who may come into contact with the water and safe for animals and humans to consume the irrigated crops In 1989 the World Health Organization adopted a standard defining minimal *biological* quality standards for reuse of treated wastewater effluents in agriculture and aquaculture The 1989 standard is found in Annex 1 (Ref 8)

1 42 CONVENTIONAL WASTEWATER TREATMENT SYSTEMS

Conventional "secondary" wastewater treatment systems use various types of mechanical equipment to supply air to aerobic bacteria that stabilize organic material and to mix the substrate with the bulk liquid The equipment includes pumps for liquids, compressors or blowers for air, rotating devices and auxiliary electrical equipment and control systems High-rate aerobic treatment sys-

tems rely either on *suspended bacterial growth*, in which the aerobic bacteria are mixed with the wastewater by mechanical stirring or injecting air into the reactor, or *attached growth* where the wastewater is exposed to bacterial films that grow on a fixed medium in the reactor A few types of systems combine both suspended and attached growth Aerobic treatment systems may be designed to support *nitrification* and *denitrification* to remove nitrogen and to remove phosphorus through biological action

Mechanically aerated wastewater treatment systems are more compact than naturally aerated systems and are capable of providing an effluent low in BOD_5 (<10 mg/l) Conventional treatment systems are used in large, medium and small scale applications for domestic and municipal wastewater effluents Conventional treatment systems that have been used in developing countries include the aerobic activated sludge process and more recent variants, including sequencing batch reactors, extended aeration and the oxidation ditch, also known as the carrousel

Conventional treatment technologies are not capable of removing pathogenic organisms as well as waste stabilization ponds The most effective conventional technology, the aerobic activated sludge process, can remove 90-99 percent of all viruses, protozoa cysts and 99 9 percent of helminth eggs, which typically is not sufficient to meet the WHO quality standard for agricultural reuse without a disinfection step (Ref 8) Waste stabilization ponds with at least 20 days retention time can typically remove 99 99 percent of viruses, 99 9999 of bacteria and all helminth eggs

Disadvantages of conventional treatment include high power consumption, high maintenance requirements and the need for close supervision by skilled operators (Ref 7) In developing countries there is a relatively sparse record of successful management compared with the simpler pond systems Developing countries could perhaps address their wastewater treatment needs more effectively by substituting, where possible, labor and land for capital and mechanical equipment

II WASTEWATER TREATMENT PROCESSES

2 1 PRELIMINARY TREATMENT

Preliminary treatment is usually defined as the conditioning of wastewater at its source before discharge into a wastewater collection system to remove or neutralize substances harmful to sewers and subsequent treatment processes Unit operations may include screening, comminution (grinding) and grit removal to prepare the wastewater for subsequent major treatment (Ref 6) These processes may also take place at the treatment plant as initial treatment measures

Some wastewater effluents may contain substances with sufficient value to make recovery worthwhile, such as protein or fats in food processing effluents or chemicals that may be reused in industrial processes In other cases removal of toxic or hazardous materials may be mandated before permitting the discharge of the effluent into a collection system

2 2 PRIMARY TREATMENT

"Primary treatment" often includes the unit processes defined as preliminary treatment It is typically the first major treatment process at a wastewater treatment plant, usually sedimentation, but not biological oxidation, of 45-70 percent of settlable solids, that removes 20-40 percent of BOD_5/COD, but little or no colloidal and dissolved matter removal (Ref 6)

A primary quality treated effluent results from various sorts of sedimentation basins, such as septic tanks, anaerobic ponds or "primary clarifiers" in conventional treatment plants The sludge is removed from the basin, treated and disposed of A primary effluent generally requires additional treatment before disposal is considered environmentally sound A primary treated effluent may be disposed of in a drain field, by land application or by irrigation of certain types of crops

2 3 SECONDARY TREATMENT

Secondary treatment is generally considered to be a level of treatment that achieves about 85 percent removal of suspended solids and oxygen consuming substances and partial stabilization of the latter Another definition specifies the quality of the effluent as concentrations of less than 30 mg/l of both BOD_5 and suspended solids, taken as a monthly average (Ref 6)

Table 2 compares the average performance and sludge production of some of the most common aerobic treatment technologies Performance varies with the quality of the effluent, temperature, process modifications and the constituents of the wastewater (Ref 5)

Table 2
Performance of Most Common Aerobic Wastewater Treatment Technologies

Treatment Technology	Removal Efficiency BOD_5	TKN	N_{total}	P	Effluent TSS	Sludge production (dry weight)
	(%)				(mg/l)	(kg/kg $BOD_{removed}$)
Primary sedimentation	20-30	5-20	0	-	-	-
Activated sludge						
high load	90	25	30	30	25	0 9-1 0
low load	95	75	55	45	10	0 5-0 7
Oxidation ditch	95-98	80-90	50-70	10-20	10-15	0 3
Trickling filter						
high load	80	20-35	25	-	45	0 6
low load	90	60-80	35	-	25	0 4
Rotating biological contactor	90-95	50-75	-	-	-	0 6
Aerated lagoon	70-80	-	-	-	-	0 03-0 08 m^3/caput/year
Waste stabilization ponds	80-90	-	50-90	-	50-75 % removal	0 03-0 08 m^3/caput/year

Source Adapted from REF 5 page 61

2 31 WASTE STABILIZATION PONDS

A stabilization pond series that holds the wastewater for 20-25 days is capable of providing a secondary quality final effluent that is also biologically safe for reuse Stabilization ponds may be classified according to the dominant biological reactions that take place in the pond anaerobic, facultative, aerobic and aerated In a warm climate a stabilization pond series 1-1 5 m deep can receive an organic loading of 40-120 kg/ha/day of BOD_5 and will produce a final effluent with concentrations of BOD_5 from 20-40 mg/l and TSS from 80-140 mg/l over a retention time of 10-40 days Although algae are necessary for oxygen production, their relatively high concentration in the final effluent is one of the most serious performance problems associated with stabilization ponds (Ref 9)

Waste stabilization ponds are attractive in developing countries because they are technologically simple and inexpensive to operate They require minimal maintenance, including periodic sludge removal, control of bank erosion and control of excess vegetation at the land/water interface and on the surface of the water

2 32 ACTIVATED SLUDGE AND RELATED PROCESSES

The activated sludge process is a *suspended growth* process in which aerobic bacteria are supplied with oxygen by mixing air with the pre-treated influent

Figure 2 illustrates the elements of a typical conventional aerobic treatment plant using the activated sludge unit process After preliminary treatment, effluent is allowed to sediment in a *primary clarification tank* for a few hours It is then transferred to a *complete mix aeration tank* (an aerobic reactor) where air is continuously pumped into the water column Periodically, a portion of the aerobic biomass is removed and allowed to sediment in a *secondary clarification tank* Part of the concentrated biomass (sludge) is returned to the aeration tank to keep the active biomass at the optimal concentration for aerobic digestion of the organic matter in the wastewater The balance of the sludge is a waste byproduct A typical conventional sludge disposal process involves *thickening, stabilization, conditioning, dewatering* and *removal* from the treatment site Stabilization can be by anaerobic or aerobic digestion, dry lime stabilization or aerobic composting Final disposal can be by landfill or land application (Ref 7)

About a third to one half of the costs of operating a conventional high-rate aerobic treatment plant are attributable to sludge handling costs (Ref 10) The aerobic sludge is mostly bacterial biomass that is still high in biodegradable material, *volatile solids*, i e, organic matter that requires further stabilization The sludge has poor settling characteristics because of the small average size of the suspended particles The volume of aerobic sludge is about five to six times that of an anaerobic sludge and requires a thickening process prior to stabilization

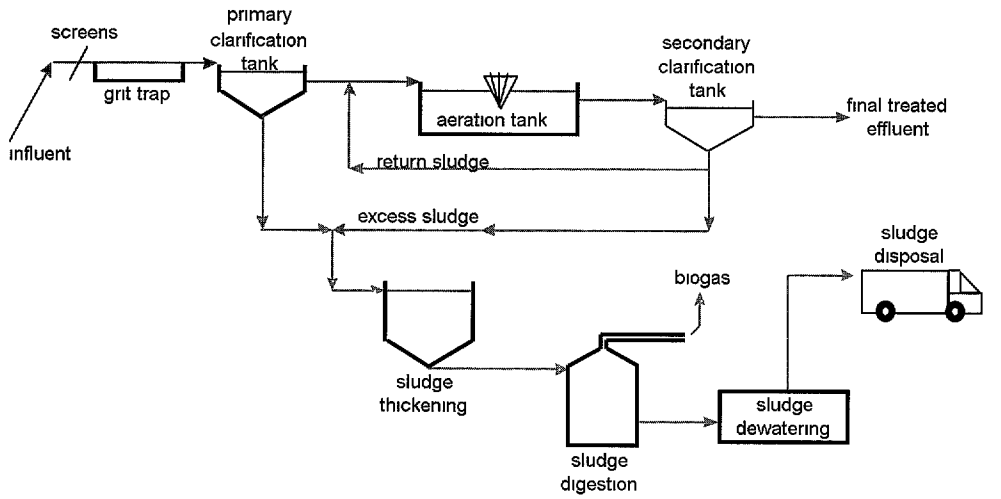


Figure 2
Schematic Diagram of a Typical Activated Sludge Treatment Plant Including Sludge Treatment by Anaerobic Digestion

2 33 SEQUENCING BATCH REACTOR

The sequencing batch reactor (SBR) process is a variation of the activated sludge process in which the aeration, sedimentation and decant steps are combined in a *single reactor*, consisting of two or more parallel tanks The process uses a five step cycle *fill, aerate, settle, draw* and *idle* During the fill stage, pre-treated wastewater mixes with the settled bacterial biomass that remains from the previous cycle The mixed liquor is then aerated mechanically, and the organic material is stabilized by aerobic digestion Aeration and mixing are stopped during the settle stage, and sedimentation of solids occurs The clarified supernatant is decanted during the draw stage, and after decanting, waste solids are removed from the bottom of the tank during the idle stage to end the cycle The cycles of parallel reactors are managed so that they operate in tandem to provide continuous treatment (Ref 7)

Although the SBR "flow through process" is easier to manage than the conventional activated sludge process and has lower O&M requirements, it still requires a skilled operator and regular maintenance The batch nature of the process prevents washout of solids, and the process is capable of handling wide variations in flow and changes in organic loading There is no need for a secondary clarifier and aerobic sludge recycle system The process is typically used for relatively small flows (up to about 11 liters per second) and is capable of providing a very good effluent quality (BOD_5, 3 3-21 mg/l, SS, 3-25 mg/l, NH_3, 0 3-12 mg/l) (Ref 7)

2 4 ADVANCED TREATMENT

Advanced, or tertiary treatment uses biological, chemical and physical processes to treat wastewater beyond the secondary stage, typically entailing removal of to 99 percent of residual suspended solids and the two major plant nutrients of significance to the sanitation sector, nitrogen and phosphorus The concern for nutrient removal is to prevent eutrophication of surface waters and to prevent nitrate accumulation in groundwater, which is harmful to small children

Nitrogen is conserved in nature, passing through a cycle of natural processes through which atmospheric nitrogen (N_2) is converted by nitrogen fixation and nitrification into compounds used by plants and animals to build protein Nitrogen is eventually returned to atmospheric nitrogen by the decay of organic material through microbial action

Nitrogen is present in wastewater in several states of oxidation as the reduced forms, ammonia/ammonium (NH_3/NH_4^+), as the partially oxidized form, nitrite (NO_2) and as nitrate (NO_3) Nitrogen is removed from wastewater by several physical, chemical and biological processes, including volatilization (stripping) of ammonia, denitrification and plant uptake

Nitrogen can be removed from wastewater through the biological processes of *nitrification* and *denitrification* The cycle begins with *ammonification*, the anaerobic biodegradation of organic nitrogen to the reduced inorganic product, ammonia Nitrification is the oxidation of ammonia to nitrate by the genus of aerobic bacteria, *Nitrosomonas*, in the presence of atmospheric oxygen Denitrification occurs in an anoxic environment, where anaerobic bacteria of the genus *Nitrobacter* reduce nitrate to carbon dioxide and nitrogen gas (N_2), which escapes to the atmosphere The processes of nitrification and denitrification can be organized as a series of aerated and anoxic zones in a treatment plant using mechanical treatment Both processes also occur in naturally aerated pond systems, constructed wetlands and in land application systems

Nitrogen may also be removed from a wastewater effluent through plant uptake as the plants convert inorganic nitrogen into proteins This occurs in ponds when algae and other plants grow and assimilate nitrogen in natural and constructed wetlands and in ponds designed as aquatic farms to cultivate floating aquatic plants Permanent removal of nitrogen through plant uptake requires regular harvesting of plant biomass to make room for new growth and to prevent recycling of organic matter and nitrogen through plant mortality and decay

Phosphorus has no known health significance in wastewater treatment, but is an important contributor to eutrophication of surface water bodies because it is the limiting nutrient for algae populations in surface water The potential removal mechanisms include adsorption by soil particles, chemical precipitation, plant uptake and other biological processes

The activated sludge process has been modified in the recent past to include nitrification and denitrification zones and "biological" removal of phosphorus through bacterial action These processes can remove approximately 80-90 percent of total nitrogen and 80 percent of total phosphorus The resulting effluent is classified as an advanced or tertiary treated effluent

2 5 ANAEROBIC TREATMENT PROCESSES

Anaerobic treatment is the use of biological processes in the absence of oxygen to stabilize organic (carbonaceous) material by conversion to methane (CH_4) and inorganic products, including orthophosphate (ortho-PO_4^{3}), carbon dioxide (CO_2), hydrogen sulfide gas (H_2S), nitrogen gas (N_2) and ammonia (NH_3) (Ref 11) Included in the process is the creation of additional anaerobic biomass

Treatment in an anaerobic reactor removes the major part of the carbonaceous oxygen demand from raw wastewater, but substantial *nitrogenous oxygen demand* remains The nutrient requirements to support anaerobic digestion are low, and the concentration of ammonium in the treated effluent reflects the concentration of organic nitrogen in the raw wastewater (Ref 5)

Some anaerobic treatment systems require mechanical mixing However, there are examples of technologically simple anaerobic reactors that are more appropriate for developing countries These simple technologies can provide effective treatment for municipal and food processing wastewaters up to an effluent quality intermediate between primary and secondary Secondary treatment is usually interpreted as attainment of at least 85 percent removal of BOD_5 and SS (suspended solids), or a secondary effluent concentration of less than 30 mg/l for BOD_5 and SS, averaged over one month (Ref 6) Depending on the composition of the raw wastewater, anaerobic reactors can achieve 65-85 percent removal of BOD_5 at 20° C (generally COD removal efficiency is 10-20 percent lower) and 60-80 percent SS removal

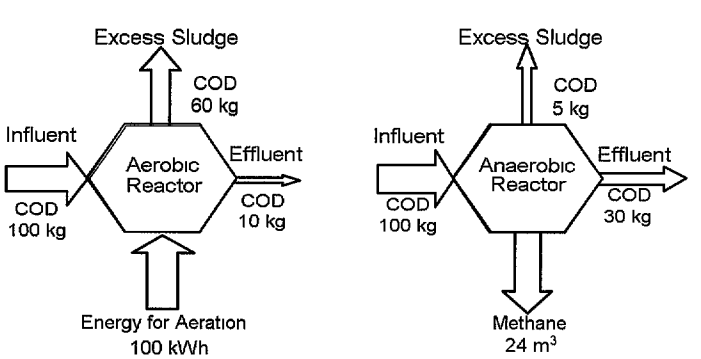


Figure 3
COD Balance and Energy Comparison Between Aerobic and Anaerobic Treatment Processes
Source Ref 12

2 6 DIFFERENCES BETWEEN AEROBIC AND ANAEROBIC PROCESSES

Figure 3 shows that aerobic digestion transforms oxygen consuming sub-

stances in the wastewater into a residual sludge The resulting sludge contains large amounts of volatile solids, mostly in the form of bacterial biomass, that require further stabilization Smaller amounts of oxygen consuming substances and solid material remain in the effluent, but the large amounts of unstable sludge mean an additional disposal problem

Anaerobic digestion results in a much smaller amount and relatively more stable sludge than aerobic processes Methane and other gases are produced, but larger amounts of residual solids and oxygen demand remains in the effluent than a typical aerobic effluent The residual sludge does not require additional treatment because it is more stable, i e , it is more thoroughly biodegraded than an aerobic sludge Anaerobic sludge has better settling properties than an aerobic sludge and is easier to dewater Where a secondary quality treated effluent is required, additional treatment is needed to remove the residual oxygen demand and suspended solids from the anaerobic enhanced primary treated effluent

Several variables determine the size and associated costs of an anaerobic reactor the rate of bacterial cell growth, the amount of bacterial biomass retained in the reactor, the organic loading and the operating temperature of the influent

2 61 CELL GROWTH

Anaerobic microorganisms are limited to a narrower temperature range and grow more slowly than their aerobic counterparts For example, none of the methane producing bacteria grows optimally below 20° C

Cellular yield is the largest difference between aerobic and anaerobic systems More than half of the organic material removed by aerobic systems can yield new microbial mass as residual sludge By comparison, cellular yield under anaerobic conditions is usually less than 15 percent of the organic substances removed (Ref 13) This means that, while an aerobic process removes more contaminants from the wastewater stream, it produces more unstable residuals that require further stabilization

Another major difference is that the low growth rate of anaerobic bacteria imposes a longer start-up period for an anaerobic reactor Typically, 50 days are required to develop a stable population of methanogenic bacteria (Ref 14) However, innoculation with "active" sludge from another anaerobic reactor can shorten the start-up time This issue is discussed in further detail in Annex 2

2 62 ENERGY RELATIONS

A third important difference is the amount of energy that mechanically aerated treatment systems consume to mix air with wastewater to support aerobic stabilization of the organic material The process involves a relatively homogenous group of aerobic bacteria and results in CO_2 and water Anaerobic digestion requires that several groups of bacteria work in concert through several stages to convert organic material into final products

Figure 4 shows the several physiological groups of anaerobic bacteria that work together sequentially to biodegrade proteins, carbohydrates and fats Also shown are the microbiological processes and energy pathways that characterize methane fermentation of organic matter Stage 1 consists of *hydrolysis* and *fermentation*, Stage 2, *acetogenesis* and *dehydrogenation*, and Stage 3, *methanogenesis* (Ref 15)

Overall methanization efficiency is limited by the individual efficiencies of each essential group of bacteria Changes in the composition and concen-

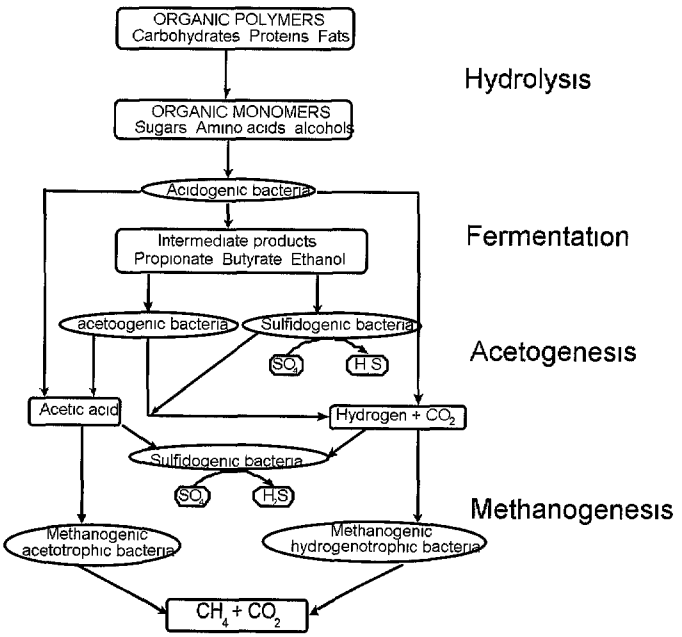


Figure 4
Flow of Carbon During Anaerobic Degradation of Organic Material
Source (Ref 15)

tration of the organic material in the reactor influent can result in reduction of COD removal rates because of limitations that can develop at any stage Slowdown at one stage can cause accumulation of biodegradable intermediate products that exit the reactor with the effluent Sulfate reducing bacteria can also reduce COD removal efficiency when the wastewater contains high concentrations of sulfates The sulfate reducers can lower methane production efficiency because they are more efficient than methanogens and can compete effectively for substrate that the methanogens depend on to complete the last stage of the anaerobic biodegradation

2 63 CELL IMMOBILIZATION AND BIOMASS RETENTION

The efficiency of an anaerobic reactor depends on the amount of bacterial biomass inside the reactor This means that accumulating and retaining the maximum amount of anaerobic biomass are key design issues for anaerobic reactors If bacteria that are washed out of the reactor and those that are lost through normal mortality are not replaced at an equivalent rate, the reaction rate will be reduced proportionally The anaerobic digestion rate of solids in wastewater is relatively slow, and if hydraulic retention time is not decoupled from solids retention time, the size of the reactor will have to be very large (Ref 13)

Consequently, to minimize the volume of an anaerobic reactor, it should be designed to have a long solids (bacterial biomass) retention time and as short a liquid retention time as possible There are several approaches to this challenge

- Filling the reactor with a *carrier* that resists wash-out, a solid medium, such a pellets, disks, strips, etc , to which a film of bacteria attach themselves firmly, (Ref 13)
- Distributing and regulating hydraulic inflow so that a bacterial mass forms and remains suspended within the reactor, (Ref 5)
- Capturing washed-out bacterial solids and returning them to the reactor,
- Controlling solids retention time by operating the system as a sequential batch reactor

The diffusion rate of substrate within the bulk liquid depends primarily on temperature, and the digestion rate is determined by diffusion of substrate to the bacteria The main groups of anaerobic bacteria grow best when they form close, complementary, *syntrophic* associations that minimize the distance across which mass transfers take place Two examples of syntrophic associations are the *anaerobic granule consortium*, seen in suspended growth reactors, and the dense *attached bacterial films* on the surface of solid objects The dense granules have good settling properties and are more easily retained in a suspended growth reactor at higher flow velocities than less dense associations of bacteria Higher flow velocities imply shorter average hydraulic retention time and correspondingly smaller reactor volume

However, formation of *granular* sludge in the UASB reactor is not common in complex wastewaters with high concentrations of suspended solids, such as typical municipal wastewater effluents Instead, the growth of the anaerobic bacteria will be dispersed among the large numbers of suspended particles, forming a *floccular* sludge, and the granulation phenomenon will either be retarded or absent (Ref 16) Stabilization of the particulate organic matter requires a relatively long residence time in the reactor, and lower flow velocities are used to minimize loss of bacterial biomass (Ref 5)

2 7 BYPRODUCTS

Anaerobic digestion produces *biogas*, a mixture of mostly methane (ranging from 60-95 percent depending on the composition of the wastewater), carbon dioxide, ammonia, nitrogen gas and hydrogen sulfide Hydrogen sulfide is corrosive to the conveyance system at concentrations ≥ 1 1 mg/l (Ref 18) With appropriate treatment to remove hydrogen sulfide, the biogas may be used as a fuel for engines to power electrical generators It may also be may be compressed and recirculated to the reactor to increase mixing intensity However, the investment in gas collection and handling systems is usually not economical unless the scale of the plant is larger than 10-15 MLD1 (million liter per day), capacity, corresponding to populations of between 75,000-100,000 (Ref 5)

Anaerobic digestion produces a well-stabilized sludge that has small concentrations of residual nutrients Dewatering the anaerobic sludge on drying beds is the final step before it is ready for disposal, except for destruction of residual pathogens The sludge cake will be fully dry in a few days and may be processed to destroy parasites so that it may be safely used as a soil conditioner Potentially pathogenic bacteria are quickly killed by drying and exposure to sunlight and air, but the dried sludge is likely to contain helminth eggs that can remain viable for up to a year Dried sludge cake is risky for farmers to handle or to apply to crops until it has been either (a) stored for up to a year, or (b) *aerobically* composted until no viable helminth eggs are detectable, generally

between 30-40 days, depending on the ambient temperature It might be worthwhile to investigate the effectiveness of heating the sludge during decantation to kill helminth ova, using the methane generated by the reactor

2 8 TYPES OF ANAEROBIC REACTORS

Anaerobic reactors may be classified as *suspended growth* when the bacteria are suspended in the bulk liquid or *attached film* when the bacteria are attached as dense films to solid media within the reactor Both types of reactors may be further categorized according to the efficiency of digestion as *low* and *high* rate

The septic tank is the most familiar low rate anaerobic reactor and one of the most common Others include the Imhoff tank, the anaerobic filter, anaerobic ponds and biogas-producing *digesters* that are typically used in farm waste management to dispose of manures and crop residues and to provide a fuel for on-farm use and composted sludge as a soil conditioner

2 81 LOW RATE REACTORS

The septic tank is most often used for single households or small groups of houses where no wastewater collection system exists Septic tanks are essentially sedimentation basins designed to remove 90-98 percent of settlable solids and 40-60 percent of BOD_5 during an average hydraulic retention time of several hours to a couple of days A septic tank is usually a single tank with a baffle on the inlet side and one on the outlet side More baffles may be included to improve sedimentation of settlable solids The solid material accumulates on the bottom of the tank and is slowly digested, often over several years, before the accumulated sludge needs evacuation The primary quality effluent is generally allowed to percolate into the ground through a subsurface drain field, or may be collected in a small bore effluent drainage network for further treatment Figure 5 illustrates the elements of a septic tank

The anaerobic filter was developed early in the Twentieth Century as a modification of the septic tank, incorporating a solid medium (rocks) on which a film of anaerobic bacteria can grow The attached film is resistant to washout of bacterial cells from the reactor An anaerobic filter treating domestic wastewater can remove about the same amount of BOD_5 as a septic tank and is more effective at removing suspended solids When overgrowth of bacterial biomass occurs, however, the filter can become clogged

Treatment systems consisting of a septic tank followed by an anaerobic filter were studied in detail in the 1950s (Ref 19) and are currently used in Brazil for flow rates up to 75 m^3/day, corresponding to a population of 500 The system is capable of providing an effluent with about 140 mg/l COD and low in suspended solids (Ref 20)

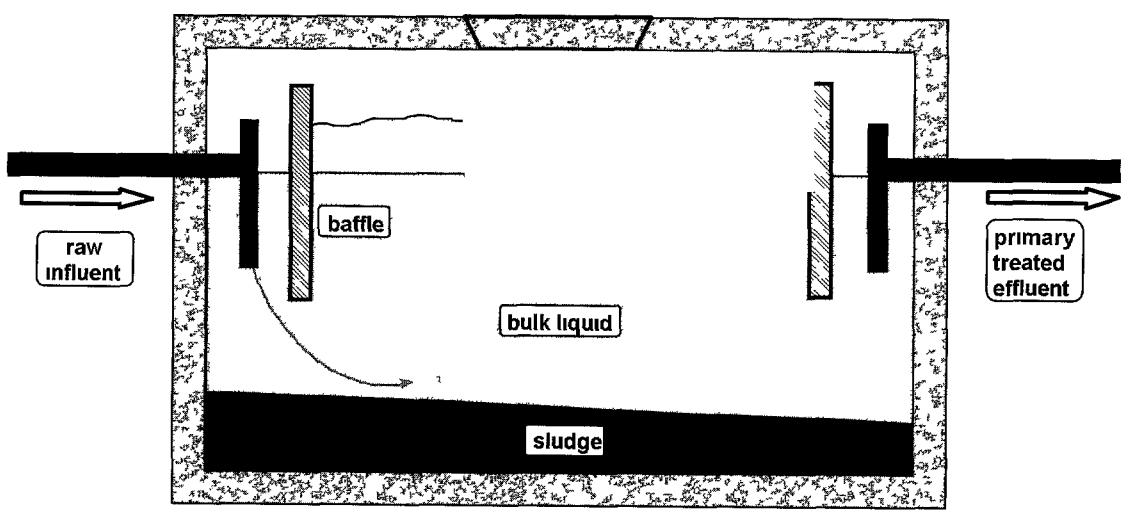


Figure 5
Cross Sectional View of a Typical Septic Tank Design

2 82 HIGH RATE REACTORS

High rate *suspended growth* reactors have been applied to treat concentrated industrial effluents, such as those of the food processing industry Two examples are the *anaerobic contact reactor* and the *upflow anaerobic sludge blanket* (UASB) reactor

The anaerobic contact reactor is the anaerobic analogue of the aerobic activated sludge process that has been used widely in industry Both feature constant mechanical mixing of the substrate within the bulk liquid and recycling to the reactor vessel of bacterial solids recovered from the effluent The anaerobic contact reactor has been used extensively in the food processing industry to treat the typically high strength effluents with relatively high suspended solids It is not used to treat municipal wastewater because the relatively low organic content implies a very large volume to achieve the necessary solids retention time

The UASB reactor is a high rate suspended growth reactor that has been applied successfully in the 1990s in large scale to the treatment of municipal and mixed industrial and the relatively more dilute domestic wastewater effluents

The high rate *attached film* reactors employ a granular solid medium as a *carrier* through which the wastewater stream flows, usually from the bottom upwards The bed of granular particles may be *expanded* or *fluidized* by a regulated upflow velocity of the influent This type of reactor can develop much higher bacterial densities than the suspended growth type of reactor and has been demonstrated to be the more efficient at COD removal rates (on the order of 80 percent)

The high rate attached film reactor type has not so far been demonstrated for municipal wastewater treatment in a typical developing country setting The main reason seems to be the relatively more demanding operational requirements than the UASB, including sophisticated feed inlet distribution, high rates of effluent recycle and the requirement for a primary treatment step upstream of the reactor

2 9 ADVANTAGES AND LIMITATIONS OF ANAEROBIC TREATMENT

2 91 ADVANTAGES

Anaerobic treatment of wastewater is an effective enhanced primary treatment option for developing countries, particularly those with mild climates, and has important advantages over aerobic processes

- Anaerobic reactors are simple to build and operate and have lower capital and operating costs,
- Anaerobic digestion is a passive process that can be operated with little or no externally supplied energy,
- High strength waste streams can be treated efficiently at no energy penalty,
- Anaerobic systems withstand shock loads better than aerobic systems,
- Large diurnal flow variations and even prolonged shutdown are not problematic,
- Anaerobic digestion reduces organic nutrients to inorganic forms that are readily available for plant uptake, a feature that makes aquatic farming systems ideal for nutrient removal,
- Low amounts of residual sludge by-product,
- Sludge has good settling properties and is easily dewatered,
- No need to treat residual sludge, (See Annex 3)
- Production of methane-rich biogas fuel that may be economical to utilize for large scale facilities (>100,000 population equivalent),
- Anaerobic processes can attenuate or degrade many refractory organic compounds so that they are less toxic, no longer toxic or no longer available to threaten water quality,
- Anaerobic treatment can be managed with relatively less skilled employees than required for conventional treatment plants,
- Anaerobic treatment provides virtually complete stabilization of organic material to CO_2 and methane

(Ref 5, 10, 11, 12, 13, 15, 20, 22, 23, 24, 25, 34)

2 92 LIMITATIONS OR DISADVANTAGES

- Optimal reactor temperature is 20° C and above, (the lower limit of currently applied anaerobic technology in developing countries is influent temperatures above 12° C),
- Longer startup time because of the slow growth rate of anaerobic bacteria,
- Additional treatment is required to meet secondary quality standards in terms of oxygen consuming substances,

- Odor control measures are more important than for aerobic treatment,
- Methanogenic activity may be inhibited from the toxic effects of high concentrations of heavy metals, toxic organics, free ammonia (> 50 mg/l) and free H_2S (> 250 mg/l),
- Chemical buffering may be required to maintain alkalinity in reactor,
- Corrosion resistant materials, such as plastics and masonry coatings are required for the reactor vessel and pipes

(Ref 5, 10, 11, 12, 13, 15, 20, 22, 23, 24, 25, 34)

III ANAEROBIC TREATMENT IN DEVELOPING COUNTRIES

3 1 UPFLOW ANAEROBIC SLUDGE BLANKET (UASB) REACTOR

The UASB is a high rate suspended growth type of reactor in which a pre-treated raw influent is introduced into the reactor from the bottom and distributed evenly "Flocs" of anaerobic bacteria will tend to settle against moderate flow velocities The influent passes upward through, and helps to suspend, a blanket of anaerobic sludge Particulate matter is trapped as it passes upward through the sludge blanket, where it is retained and digested Digestion of the particulate matter retained in the sludge blanket and breakdown of soluble organic material generates gas and relatively small amounts of new sludge The rising gas bubbles help to mix the substrate with the anaerobic biomass The main elements of the type of UASB reactor discussed in Annexes 2 and 3 are illustrated in Figure 6

The biogas, the liquid fraction and the sludge are separated in the gas/liquid/solids (GLS) *phase separator*, consisting of the gas collector dome and a separate quiescent settling zone The settling zone is relatively free of the mixing effect of the gas, allowing the solid particles to fall back into the reactor The clarified effluent is collected in gutters at the top of the reactor and removed The biogas has a methane content typically around 75 percent and may be collected and used as a fuel or flared

A properly designed UASB reactor eliminates the need for mechanical mixing and has few moving parts If gravity distribution of the influent is possible, the treatment plant may need pumps only to remove excess sludge from the reactor periodically for transfer to drying beds

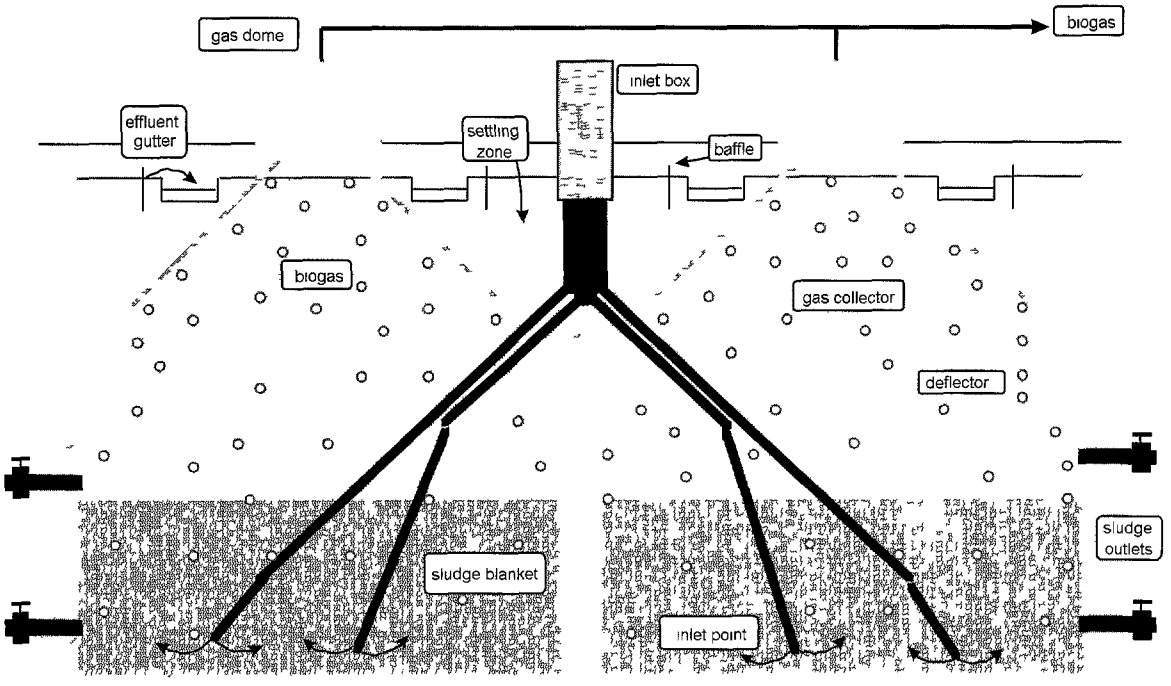


Figure 6
Schematic Cross Sectional View of a UASB Reactor

3 11 DESIGN CRITERIA FOR THE UASB REACTOR

The UASB reactor is designed around two main criteria *hydraulic retention time* (HRT), the average amount of time that the liquid part of the wastewater stays in the reactor, and *solids retention time* (SRT), the average residence time of the solids in the reactor

For a wastewater with high concentrations of suspended solids, sedimentation of the solids is the main concern The design criteria are largely dictated by the *maximum upflow velocity* that the solid particles can withstand before being washed out of the reactor, generally between 0 5 and 1 0 m/hour for municipal effluents (Ref 17)

The *solids retention time* should be long enough to allow the growth of enough anaerobic bacteria to digest the bulk of the organic material in the wastewater The optimal SRT will determine at what HRT the UASB can be operated, and the HRT will dictate the volume of the reactor

Organic loadings of up to 15 kg COD/m^3 can be applied to the UASB reactor for most types of wastewater effluents Depending on the composition of the wastewater, the removal efficiency of the UASB process may vary between 60-70 percent for COD and 75-85 percent for BOD^5, at influent temperatures between 20-35° C A UASB reactor treating a typical municipal wastewater will provide a treated effluent that corresponds to an enhanced primary treated effluent in terms of oxygen consuming substances and suspended solids Approximately 3 kg of COD can produce one m^3 of biogas, while about 5-10 percent of total COD is converted into stabilized sludge For a typical municipal wastewater effluent the solids residence time in the reactor is up to one year, while the hydraulic retention time ranges from 5-12 hours (Ref 15) Design parameters for UASB reactors are discussed in greater detail in Annex 2

3 12 EXAMPLES OF FULL SCALE ANAEROBIC TREATMENT PLANTS IN DEVELOPING COUNTRIES UASB TREATMENT PLANT CASE STUDIES

The authors visited three full scale UASB treatment plants operating in India and a large UASB facility located in Bucaramanga, Colombia These full scale anaerobic treatment plants were commissioned in the early 1990s Summaries of the characteristics of the treatment plants are provided below Annex 3 discusses the treatment plants in more detail

The government of India has made a major commitment to anaerobic treatment technology in its national river basin improvement program As of 1996, thirteen new anaerobic treatment plants, with an aggregate treatment capacity of over 306 MLD [1] (million liter per day), are under construction in India (Ref 21) The treatment plants described below have been in operation long enough to be able to evaluate their treatment effectiveness and their financial and economic costs and benefits

- A 5 MLD plant in Kanpur, in the state of Uttar Pradesh, built in the late 1989, was the pilot project that demonstrated the feasibility of the UASB reactor for municipal wastewater treatment in India The plant consists of two UASB units with a total volume of 1,200 m^3, followed by a facultative pond for post-treatment that has a retention time of 24 hours The initial COD concentration in the influent averages 560 mg/l, and the removal efficiency of the reactor is approximately 74 percent The removal efficiency for suspended solids is 75 percent No use is made of the biogas The treatment plant is still in operation as of 1996 with few modifications (Ref 17)

- A 14 MLD plant in Mirzapur, Uttar Pradesh, based on the Kanpur pilot plant design, was commissioned in 1991, serving a population of about 130,000 The concentration of organic material in the raw wastewater averages about 360 mg/l for COD The plant consists of two UASB units of 2,400 m^3 each, followed by facultative ponds for post-treatment, with a retention time of 24 hours The final effluent contains from 70-130 mg/l of COD, representing an average removal efficiency of about 81 percent The plant has enough biogas to generate 70 kW of electrical power daily, but needs only an average 12 kW per day for plant operation Two generator sets of 18 kW each are powered by dual-fuel diesel engines, while excess gas is flared The capital cost of the treatment plant, including the facultative ponds used for post-treatment was about $650,000 ($5/caput), or about $46,500 per MLD of treatment capacity Annual operating costs are about $4,000 ($0 03/caput) (Ref 17)

[1] One MLD = 0 263 million US gallons/day

- A 36 MLD plant in Kanpur reached full performance in 1994, treating a mixture of up to 75 percent municipal wastewater and 25 percent tannery effluent The COD concentration of the combined influent ranges from 1,100-2,500 mg/l The COD removal efficiency of the reactors ranges between 55-60 percent The capital cost of the UASB reactors was $3 96 million (about $8/PE) and $1 87 m for the aerobic post-treatment facility that is under construction Overall operating and maintenance costs of UASB reactors are around $0 6 million/year, of which $0 23 million is paid back by electricity generation (Ref 16)

- The COD concentration of the mixed influent is about 7 times that of the Mirzapur municipal wastewater, analogous in terms of the amount of COD to municipal wastewater from a population of over 900,000 Comparing the two, the capital cost of the Mirzapur reactors was about $129/kg of COD removal capacity, while the Kanpur reactors was $44/kg of COD removal capacity The operating costs per unit of COD removed was $2 17/metric ton for Mirzapur and $11 26/metric ton for Kanpur The difference in operating costs is attributed to the more numerous mechanical and electrical components of the Kanpur plant and greater management requirements of a more complicated system

Colombia was the site of an early UASB research project that led to the current state-of-the-art design for the three Indian plants visited and the Bucaramanga treatment plant described below

A 42 MLD peak capacity anaerobic treatment plant serves a population equivalent of 230,000, about 1/3 of the total population of the city of Bucaramanga, Colombia The plant consists of three UASB reactor modules and two facultative ponds for post-treatment Reactor removal efficiencies are 65, 75 and 70 percent for COD, BOD^5 and TSS respectively and 75, 90 and 90 percent for the final effluent The investment cost of the plant was about $3 2 million, including land ($13 90/caput) Annual operating costs are about $100,000 ($0 43/caput or $0 008/$m^3$) The biogas is collected and flared Two more facilities of the same design and similar scale are under consideration to complete the city's wastewater treatment needs (Ref 22, 23)

3 2 HYBRID REACTORS

3 21 HYBRID BAFFLED/UASB REACTOR (REF 24)

Researchers at the University of the Andes in Bogota developed and demonstrated a hybrid anaerobic reactor that has a relatively high COD removal efficiency (around 70 percent) in the sub-optimal temperature range for methanogenic bacteria below 20° C The purpose of developing the reactor was to make anaerobic treatment of municipal effluents feasible in the range from 13-20° C that prevails on the plateau on which Bogota is located The reactor geometry imposes a *plug flow* hydrodynamic regime on the wastewater Alternating vertical baffles force the fluid alter-

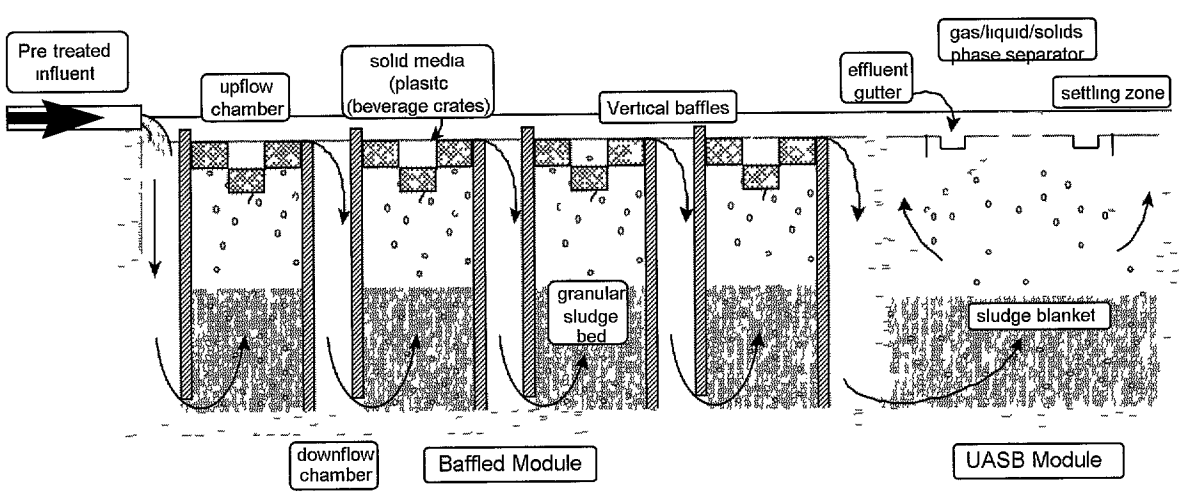


Figure 7
Cross Sectional View of Hybrid Baffled Plug Flow/UASB Reactor

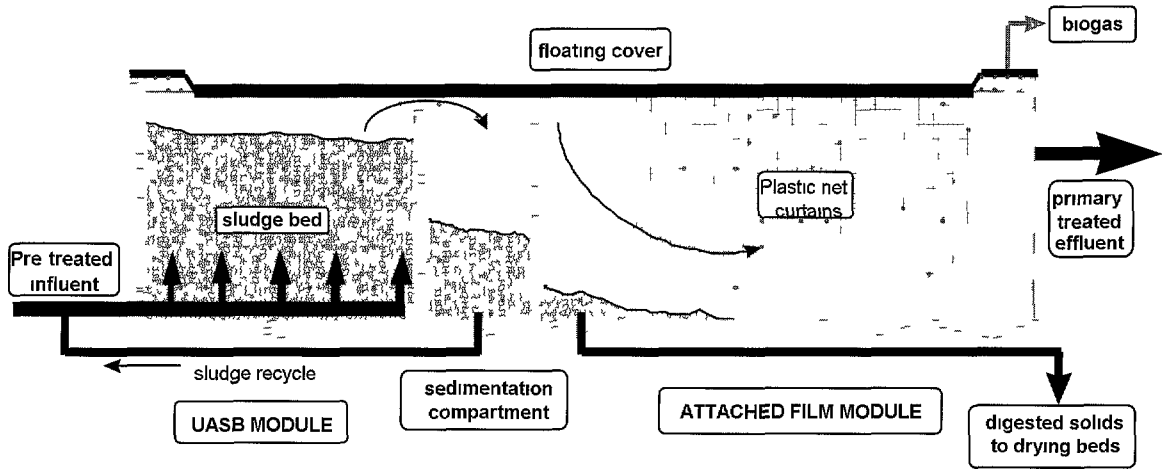


Figure 8
Cross Sectional View of Hybrid UASB/Attached Film Reactor

nately upward and downward before it enters a final UASB compartment Figure 7 is a schematic diagram of the hybrid reactor

The kinetics of the "RAP" reactor (the acronym for "plug flow anaerobic reactor" in Spanish) favors granulation of the anaerobic bacteria The granular sludge has better settling characteristics than floccular sludge so that biomass accumulates in the upflow compartments of the reactor at higher flow velocities, while lighter particles are washed out The granular sludge is preferred because the metabolic activity is double that of floccular sludge The working hypothesis explaining the good performance of the RAP reactor in the suboptimal temperature range is the greater accumulation of active biomass and the higher metabolic rate of the biomass than is common in a typical single stage UASB

The upper surface of the RAP reactor may be either open or enclosed to capture gases If open, gases will escape to the atmosphere To aid in separating gas bubbles from solid particles in the baffled module, solid media are placed just below the surface of the wastewater These are standard PVC plastic beverage crates, with alternating voids and solid surfaces The effluent has a reduced gas content when it reaches the UASB compartment, which is thought to enhance phase separation

The RAP reactor is simple to build it consists of a concrete tank with removable vertical baffles and a final UASB compartment The UASB compartment provides separation of the gas/liquid/solid phases and removal of the clarified effluent in gutters The flow is distributed within the UASB compartment through a horizontal slot on the upstream side of the reactor, eliminating the overhead distribution from splitter boxes and manifold pipes that are common in the reactors seen in Bucaramanga and India Six RAP reactors have been commissioned in Colombia as of 1996, the largest of which is about 4 MLD capacity, located in Ubate, serving a population of about 60,000

3 22 HYBRID UASB/ATTACHED GROWTH REACTOR

An EPA-sponsored demonstration project located in Maryland evaluated the performance of an anaerobic reactor that provided enhanced primary treatment in a system treating pre-treated wastewater from the Frederick County treatment plant The treatment objective, advanced quality final effluent, was met for all criteria except for phosphorus removal (Ref 25) The hybrid reactor, a schematic diagram of which is presented in Figure 8, incorporates both basic types of anaerobic processes in one unit *suspended growth* and *fixed film, attached growth*

- The first compartment contains a UASB reactor (without the three-phase gas/liquid/solids separator) that digests primarily particulate organic material, which is retained and digested over a retention time of up to one year Gases are collected under the floating cover
- The final compartment contains a solid medium on which a bacterial film forms The attached growth process is capable of

digesting soluble and colloidal organic matter that is less readily retained and degraded in a suspended growth reactor

The designers of the hybrid reactor, Sunwater Systems, call it an "anaerobic bioreactor" It is a simple design that resembles a septic tank It features a tank with two or three compartments, built with masonry walls on a concrete slab and a rubber or polyethylene cover that floats on foam blocks There is no gas/solids/liquid phase separator in the UASB reactor module, gas collects at the periphery of the cover and passes through a soil filter to remove odors and discharged through a vent pipe Polypropylene net curtains are suspended in the compartment downstream of the UASB module The purpose of the netting is to provide a solid medium on which anaerobic bacterial film can grow The crossflow of effluent from the UASB module brings dissolved and colloidal organic material into close contact with the attached growth film

The average quality of the raw wastewater influent was high strength by US standards COD 1,285 mg/l, BOD_5 434 mg/l, and TSS 500 mg/l, and the temperature of the influent ranged from a high of about 19° C to a low of about 17° C over the seasonal cycle The average performance of the reactor was adequate, despite the suboptimal temperature for anaerobic digestion Removal efficiencies for pollutants were as follows 65, 63 and 83 percent for COD, BOD_5 and TSS respectively The constant flow rate of preliminary treated wastewater influent was about 0 152 MLD, and the average HRT was about 16 hours (Ref 25)

The other elements in the demonstration project provided further treatment to the enhanced primary treated effluent from the anaerobic reactor by means of aerated tanks and anoxic zones for nitrification and denitrification and a subsurface flow marsh for final polishing The anaerobic reactor removed approximately 65 percent of the pollutants, and cost approximately $40,000, or about $263/m^3$ of daily treatment capacity

3 3 OPTIONS FOR POST-TREATMENT OF ANAEROBIC REACTOR EFFLUENTS

Aerobic treatment of an anaerobically treated enhanced primary effluent stabilizes the residual oxygen demand in the highly reduced effluent and can be designed to remove significant amounts of nutrients

Although anaerobic reactors are effective at stabilizing organic material by degrading carbonaceous oxygen demand to methane and carbon dioxide, a typical anaerobic enhanced primary effluent has substantial residual oxygen demand, mostly from the reduced form of nitrogen, ammonia The readily oxidizable residual oxygen demand may be dealt with in an additional aerobic treatment step or conversion to plant biomass in an integrated treatment and production system

A normally functioning UASB reactor can remove an average of 65 percent of COD (range 50-75 percent), 80 percent of BOD_5 (range 70-90 percent) and 75 percent of suspended solids (range 60-85 percent) (Ref 5) Beginning with a typical municipal raw wastewater, this level of treatment will generally result in a treated effluent that corresponds to an "enhanced primary" quality, intermediate between primary and secondary (between 30-70 mg/l for BOD_5) (Ref 6) An effluent less than secondary quality will generally not meet environmentally sound effluent discharge standards and will definitely need further treatment to be safe for reuse in agriculture The post-treatment should be designed to improve the effluent quality in the following parameters

- pathogen contamination (measured by the index of *E coli*),
- residual organic material (COD/BOD_5),
- oxygen demand from the reduced forms of N and S,
- residual suspended solids (TSS)
- inorganic N and P (nutrients)

Besides the carbonaceous end products, methane and CO_2, soluble, inorganic nutrients are the end products of anaerobic biodegradation of organic material The mineralized nutrients, ammonium (NH_4^+) and orthophosphate (o-PO_4^{3-}) are *primary growth nutrients* that are readily assimilated by heterotrophic bacteria and plants, including algae and higher plants These may be removed by physical processes, such as volatilization and precipitation and aerobic biological processes, such as nitrification (and subsequent anaerobic denitrification) that complement anaerobic treatment to improve the quality of the final treated effluent The means of aeration may be either mechanical, as in the activated sludge process, oxidation ditch and sequencing batch reactor options, or passive, as in waste stabilization ponds or constructed wetlands

Post-treatment can also designed to exploit the economic value of the nutrients by converting them into commercially valuable plant biomass The effluent from an anaerobic reactor is a renewable source of water, major plant nutrients and

trace nutrients, or *micronutrients*, that can support aquatic farming systems and can be used to irrigate terrestrial crops

Aquaculture-based wastewater treatment systems have been developed in the recent past that can provide post-treatment to an anaerobic effluent to advanced quality standard (Ref 26, 27) Integrated treatment and production systems can provide not only indirect benefits, such as environmental and health improvements, but also direct financial benefits sales of reclaimed water and agricultural products

Conventional processes of nitrogen removal from wastewater include *nitrification* and *denitrification*, ammonia stripping and ion exchange None of those processes are designed specifically to take advantage of the resource value of the nitrogen Phosphorus removal by conventional processes includes chemical precipitation and adsorption, more recently, biological removal of P has been developed as a modification of the activated sludge process These processes are not designed to exploit the full value of the phosphorus, except for a small residual in sludge that may be used as a soil conditioning product in agriculture and horticulture

3 31 ANAEROBIC REACTORS IN SERIES WITH MECHANICALLY AERATED TREATMENT SYSTEMS

Where skilled manpower and a reliable electric power supply are available, but not enough affordable land for pond systems, the investment and operating costs of conventional mechanically aerated treatment plants may be reduced by using anaerobic reactors as the initial major treatment process Research in Brazil demonstrated that using an anaerobic reactor in series with a mechanically aerated post-treatment process has several important advantages (Ref 28)

- The volume of the anaerobic/aerobic treatment plant will be about half the volume of a conventional activated sludge plant, illustrated in Figure 2, reducing the capital cost correspondingly
- The demand for electric power for mechanical aeration is reduced by more than 50 percent, reducing operating costs,
- The anaerobic reactor replaces both the primary clarifier and the sludge digester of a conventional system Excess aerobic sludge can be recirculated to the UASB reactor, where it will be stabilized and densified, facilitating sludge handling,
- Nitrification and denitrification (alternating aerobic and anoxic) zones can be included to remove nitrogen, and the anaerobic sludge can provide a carbon source to support denitrification

The oxidation ditch is also an option for post-treatment of an anaerobic effluent It is a secondary treatment process that is less difficult to manage than the activated sludge process It uses an oval channel with a rotor placed across it to provide aeration and circulation The screened wastewater in the ditch is aerated by the rotor and circulated at the rate of 0 3-0 6 m/second The oxidation ditch is a lower rate process that produces less residual sludge It has the further advantage of providing full nitrification (oxidation of all of the ammonia to nitrate) when designed on the basis of the nitrogenous oxygen demand (NOD) in the reactor effluent (Ref 5) The size and power consumption of an oxidation ditch used for post-treatment of an anaerobic effluent will be smaller than one that treats the raw wastewater

3 32 TRICKLING FILTER

The trickling filter is an aerobic attached growth process that distributes settled wastewater or an anaerobic effluent over solid media, such as rock, broken brick or plastic Attached films of aerobic biomass grow on the media and digest the organic material in the wastewater Periodically, excess biomass sloughs off the media and is collected for disposal in a secondary clarifier Part of the clarified effluent is recirculated over the filter to increase hydraulic scour to keep the fast growing biomass in check The aerobic sludge byproduct of the trickling filter may be combined with the raw wastewater influent and digested in the anaerobic reactor that is used as the initial treatment step, increasing the organic loading to the reactor and improving its removal efficiency

The trickling filter process is a simple and robust process that can operate at high or low loads With recirculation, it can remove 80-90 percent of BOD_5 and 25-35 percent of total nitrogen In warm climates the trickling filter may become infested with flies, and may be the source of odors

3 33 LOW ENERGY POST-TREATMENT TECHNOLOGIES

Since anaerobic treatment needs little electric power, other than small amounts for pumping within the treatment plant, it would be reasonable in a developing country to select a post-treatment process that can also operate with little or no

power supply Pond technologies meet that requirement, receiving the energy needed for the biological treatment processes directly from sunlight and oxygen from natural rearation from the atmosphere through the surface of the pond Similarly, subsurface flow wetlands rely on attached films of aerobic bacteria that receive oxygen from the vascular system of the plants through the roots

3 34 WASTE STABILIZATION PONDS FOR POST-TREATMENT OF ANAEROBIC REACTOR EFFLUENTS

Stabilization ponds may be used to treat wastewater effluents typically to secondary quality, beginning with raw wastewater, or they may be designed to treat effluents at any stage of treatment A pond system can polish an anaerobic enhanced primary treated effluent and, with appropriate retention time, can remove pathogens to an acceptable level before discharge into a receiving stream or before reuse for irrigation or groundwater recharge

Brazilian researchers have developed design criteria for pond systems that provide effective post-treatment of anaerobic reactor effluents in a warm climate (Ref 29) These design criteria are described in the following paragraphs

The substantially reduced oxygen demand and solids content of an anaerobic reactor effluent make it possible to reduce the pond area by half or more compared with a conventional pond system that receives raw wastewater It has been established empirically that initial anaerobic treatment facilitates the removal of nitrogen and phosphorus by means of physico-chemical processes (volatilization and precipitation) that develop in the pond An anaerobic reactor substitutes for the initial cells in a conventional pond series that are designed to stabilize organic material The effect is to reduce the overall pond area, and the post-treatment ponds are optimized to destroy pathogens and to remove residual oxygen demand and nutrients

Application of a *plug flow* hydraulic regime for post-treatment ponds reduces the pond space needed by 50-65 percent compared with a pond series that would normally be designed for polishing The size reduction is more than 80 percent compared with a conventional series of 4-5 ponds designed to receive raw wastewater A plug flow pond system for post-treatment can be designed to maximize algae growth, so that photosynthesis by algae predominates over bacterial growth Light can penetrate almost all of the water column in a shallow pond (0 3-0 65 m depth) because of the relatively low turbidity of the reactor effluent The production of CO_2 during photosynthesis elevates the pH of the water significantly during the middle

Table 3
Variations in Characteristics of Wastewater in a Plug Flow Series of Four Ponds with 0 65 m Depth and Retention Time of Five Days Each[1]

Parameter	Units	UASB (HRT 7 2 hr) Influent	UASB (HRT 7 2 hr) Effluent	Pond number I	Pond number II	Pond number III	Pond number IV
E coli[2]	(per 100 ml)	$2\ 7 \times 10^7$	$9\ 0 \times 10^6$	$3\ 9 \times 10^5$	$9\ 8 \times 10^3$	$7\ 7 \times 10^2$	$1\ 0 \times 10^2$
E coli	(log 10)	7 44	6 96	5 59	3 99	2 89	2 01
helminth ova	(ova/l)	16,093	1013	3 9	ND[3]	NA[4]	NA[4]
BOD_5	(mg/l)	726	88	55	46	45	40
COD	(mg/l)	1,271	314	190	223	210	249
suspended solids	(mg/l)	422	63	53	73	52	50
TKN	(mg/l)	63	53	29	16	5 8	3 1
P	(mg/l)	7 3	9 0	9 4	6 7	3 4	1 2
alkalinity	(meq/l)	6 2	8 4	6 8	6 0	5 2	4 8
pH		7 6	7 0	7 7	8 5	9 1	9 4
DO[5]	(mg/l)	-	-	2 8	7 5	>10	>10
$Chlorophyll_a$	(µg/l)	-	-	673	833	673	878

[1] Source Ref 28 [2] *Escherichia coli* One of the species of bacteria in the fecal coliform group that is used as an indicator organism for the presence of less easily detected pathogenic bacteria (Ref 6) [3] ND = not detected [4] NA = not analyzed [5] DO = dissolved oxygen measured in the middle of the water column

part of the day, particularly in a well-buffered water body

At pH values between 9-10, ammonium ions (NH_4^+) are converted to free ammonia (NH_3), which volatilizes as a gas The plug flow post-treatment ponds are designed to achieve high pH values (above 10) during the day, resulting in ammonia stripping and phosphate removal by precipitation, typically as salts of calcium or magnesium, depending on the composition of the wastewater The plug flow post-treatment pond system is an efficient and reliable process to remove nutrients from the effluent of an efficient anaerobic system, providing that an elevated pH is established in the pond Table 3 shows nutrient removal rates in experiments conducted in Brazil (Ref 29)

A high pH accelerates the rate of die-off of *E coli* in the pond (Ref 8) Experiments indicate that the die-off constant is approximately inversely proportional to the depth of the pond *Once the detention time is proportional to the depth, the area of the system is essentially independent of the depth for whatever removal efficiency desired* (Ref 29)

The anaerobic reactor is capable of removing 90 percent of coliform bacteria, the indicator organisms for presence of pathogenic bacteria (Ref 5) Table 3 shows the variations in characteristics of wastewater in a plug flow post-treatment pond system consisting of four ponds, 0 65 m deep, with a detention time of five days per pond The pond series was capable of reducing fecal coliforms (indicated by a specific fecal coliform organism, *E coli*) in the reactor effluent to levels that meet the 1989 WHO standard for water reuse for agricultural purposes (fecal coliforms ≤ 1,000 most probable number per 100 ml and ≤ 1 helminth egg per liter) The desired fecal coliform reduction was reached in the third pond, making the fourth redundant The same effect was seen in a pond series with the same surface area but half the depth and retention time (0 32 m depth and 2 5 days retention time each) the number of *E coli* were reduced to acceptable levels in pond number three despite the differences in depth and retention time Shallow ponds may require special measures to suppress the growth of unwanted emergent macrophytes that could interfere with the treatment process

If the pond effluent is to be used in *fish culture* its minimum acceptable biological quality should be no more than 1×10^5 fecal coliforms per 100 ml in order to maintain a fish pond water quality no more than 1×10^4 FC/100 ml That quality pond water will assure that that the fish will be free of pathogenic parasites, bacteria or viruses (Ref 2) According to Table 3, this effluent quality could be expected from the shallow plug-flow type of ponds with a surface area intermediate between the total area of ponds I and II The additional detention time in the fish ponds will provide further treatment, and the system can be optimized to assure adequate biological quality of the effluent from the fish ponds, so that it is suitable for reuse in agriculture

3 35 CONSTRUCTED WETLANDS (REF 9)

Wetlands can be the site for most biological and physical treatment processes, such as microbial degradation of organic material, sedimentation of suspended solids and removal of pathogens They also function as *sinks* where mineralized nutrients are fixed in plant biomass or removed through the processes of adsorption, precipitation, nitrification and denitrification

The soil in wetlands is saturated with water for all or most of the year and colonized by aquatic vegetation, including *macrophytes* (higher plants) and bacteria Natural wetlands differ in the dominant types of vegetation native to each *swamps* have mostly trees, *bogs* have primarily mosses and peat, and *marshes,* that are characterized by grasses, other emergent macrophytes and floating macrophytes Marshes are the most common type of wetland used for wastewater treatment

Constructed wetlands have a controlled hydraulic regime, a graded bottom and provision for management of vegetation and other system components There are two main types of constructed wetland, according to the position of the water surface with respect to ground level *free water surface* and *subsurface flow*

The water surface in a free water surface wetland is exposed to the atmosphere, where reaeration occurs, and the emergent vegetation is rooted in the soil at the bottom of the excavated basin Operating depths range from 0 3-0 8 m and retention times up to several days

A subsurface flow wetland has *porous media,* such as gravel, filling the excavated basin to a depth of 0 3-0 6 m, and the surface of the water is maintained below the surface of the media The same types of emergent plants as in the free water surface wetland are rooted in the gravel

Microbial films grow on the surfaces of roots and media in constructed wetlands and are the sites of active biological treatment, mediated by temperature, oxygen availability and by the *surface area of*

the attached growth Oxygen is transported by the vascular system of the plants, from the leaves to the roots to the microbial films that colonize the roots and media

Constructed wetlands can remove large amounts of BOD_5, nutrients and suspended solids Maintaining high nutrient removal efficiencies through the mechanism of plant uptake ultimately depends on periodic harvesting to provide space for additional plant growth and to prevent recycling of BOD_5 and nutrients within the system

3 36 AQUATIC FARMING SYSTEMS

There has been increasing interest in recent years in using *aquaculture* systems as natural sinks for oxygen consuming substances and wastewater-borne nutrients and recognition of their capacity to provide an advanced quality final effluent

Water hyacinths (*Eichnornia crassipes*) are tropical floating macrophytes that can remove nutrients efficiently, because of the microbial colonies that form on the root system of the plants However, the low nutritional value, high ash content and high bulk of the biomass make the water hyacinth unattractive as a commercial crop plant Moreover, water hyacinths allow mosquitoes access to the water surface and provide an excellent breeding environment

The common *duckweeds* are group of floating macrophytes with excellent potential as a commercial crop plant because of their high growth rate, high nutritional value and low fiber content They are a diverse family of plants and are adapted to a wide spectrum of climatic and environmental conditions The small plants consist of a single structure, a flat, ovoid *frond*, 2-20 mm long, without stems or significant fibrous support tissue Duckweed species reproduce primarily by budding, although they occasionally flower and produce seeds They cover the water surface in a mat that shades the water column, preventing the growth of competitive plants, such as algae The duckweed mat also interferes with mosquito breeding, and the quiescent conditions under the mat are ideal for sedimentation of suspended solids (Ref 26, 27, 30)

Duckweed species belong to the *Lemnaceae* family, comprising four genera and over sixty species that are distributed worldwide They grow rapidly under ideal conditions, doubling their mass in one or two days The small free-floating plants and can be harvested by skimming *Agronomic management* of the duckweed on wastewater can result in production rates of about 300-800 metric tons of fresh biomass per hectare per year (ha/year), or the equivalent as a dried meal of about 20-40 metric tons ha/year Dried duckweed meal can substitute for equal quantities of soybean meal in balanced poultry feeds (Ref 31), and fresh duckweed satisfies the nutritional requirements of certain fish grown in ponds, such as tilapia and a carp polyculture (Ref 26)

Duckweed aquaculture can be organized and managed as a wastewater treatment system that removes residual oxygen demand, suspended solids and nutrients from a settled (primary treated) wastewater effluent (Ref 26) The productivity of duckweed farming is enhanced by initial treatment in an anaerobic reactor (Ref 27)

Wastewater treatment efficacy, duckweed production techniques and the nutritional value of the plants were verified in a pilot project in Bangladesh The project was established in 1989 and has been in continuous operation since that time, as of mid-1996 The demonstration treatment facility is located at the Kumudini Welfare Trust Hospital and nursing school campus in Mirzapur, Bangladesh The project was evaluated in 1994 by staff of the International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE), located in Delft, the Netherlands The 0 6 hectare duckweed pond system treated the wastewater from a population of about 2,500 The wastewater was a mixture of domestic and hospital wastes and was low strength in terms of organic loading Primary treatment of the raw wastewater was provided in an anaerobic pond with a retention of about three days (Ref 27)

From the anaerobic pond the effluent flowed to a serpentine channel system where the duckweed was cultivated The surface loading rate was 48-60 kg BOD_5/ha/day and the average hydraulic retention time was 20 4 days Removal rates were 90-97 percent for COD, 95-99 percent for BOD_5, and 74-77 percent for Kjeldahl N and total P The effluent contained 2 7 mg/l of Kjeldahl N and 0 4 mg/l of total P The water column remained aerobic At two thirds of retention time, the duckweed plants had absorbed virtually all ammonium (NH_4^+) and ortho-PO_4^3 ions from the water column

Leakage in the unlined channels accounted for water and nutrient loss during the dry season In a watertight pond the duckweed harvesting would remove 60-80 percent of the N and P load, or 0 26 g/m^2/day of nitrogen and 0 05 g/m^2/day of phosphorus in the first three quarters of the retention time, e g within 15 3 days Duckweed productivity has been maintained for several years at the level

of 58-105 kg/ha/day (dry weight), or 750-1500 kg/ha/day fresh weight in the dry and wet seasons respectively

The evaluation team concluded that the *microbial hydrolysis of the organically sequestered nutrients is the limiting step for enhanced duckweed biomass production* (Ref 27) This finding confirms the complementarity of initial, thorough anaerobic treatment followed by duckweed aquaculture for post-treatment

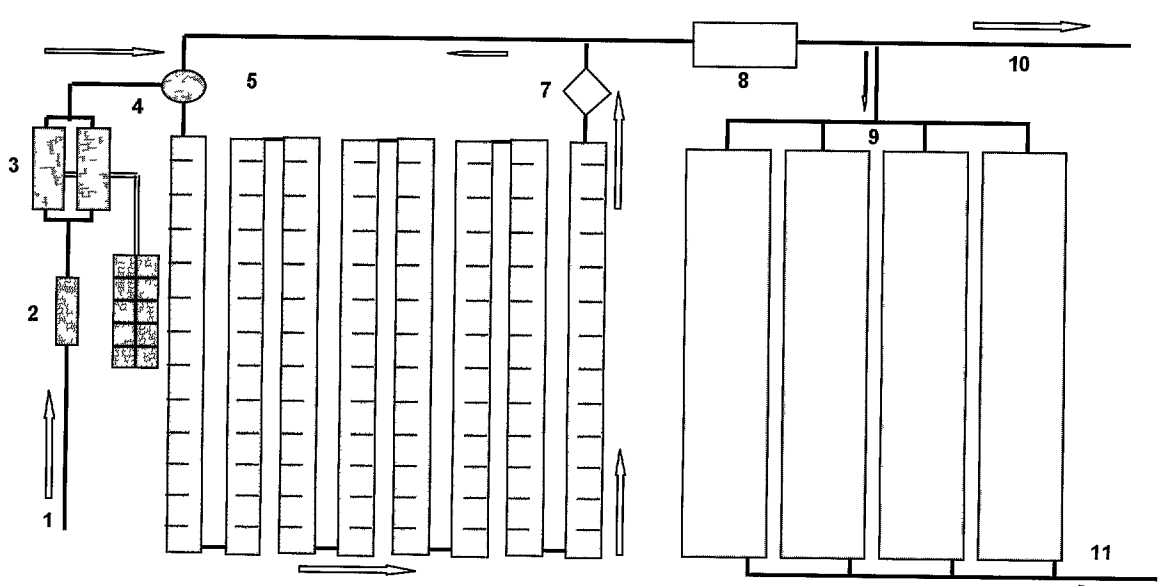
A commonly held view is that a duckweed mat covering a pond will result in a completely anaerobic water column That view was contradicted by the findings of the IHE evaluation team The explanation given by the authors was as follows

> "Despite the fact that the duckweed/water surface remained undisturbed, except for frequent harvesting, oxygen appeared consistently in ample supply, possibly because continuous oxygen transfer through the plant and root system supplements reaeration The aeration through the surface was calculated to be 3-4 g/m^2 of oxygen, which is slightly higher than transfer through an uncovered surface" (Ref 27)

The report also noted that activity of heterotrophic bacteria (that use up oxygen to oxidize COD) decreases from the upper to the lower reaches of the system, as more COD is converted aerobically

Research in Israel concluded that duckweed (*Lemna gibba*) cultivation on "settled" domestic wastewater can produce a secondary quality effluent after five days retention time that is suitable for irrigation of certain types of crops Optimal depth for the water column was about 0 3 m, and the maximum extrapolated yield reported for *Lemna gibba* was 55 metric tons per hectare per year of dry weight material Longer retention time improved the quality of the effluent in terms of nutrient concentrations and reduced the duckweed productivity because of reduced nutrient availability The economic benefit of dried duckweed meal production on wastewater was estimated to be on the order of $US 0 02-0 05/m^3 of treated wastewater (Ref 32)

Agronomic management, i e , maintaining optimal density of the duckweed mat on a primary treated wastewater effluent, optimizes both duckweed productivity and the rate of nutrient removal Adequate mineralization of the nutrients in an initial anaerobic biodegradation process makes the maximum amount of growth nutrients available to the plant crop Integration of anaerobic enhanced primary treatment of wastewater and duckweed



1 raw wastewater influent
2 screen and grit trap
3 anaerobic reactors
4 sludge drying bed
5 mixing and sampling basin
6 duckweed cultivation channel
7 recirculation pump
8 aeration basin
9 fish culture ponds
10 final treated effluent for reuse
11 fish pond effluent for irrigation

Figure 9
Schematic Diagram of a Duckweed Aquaculture Treatment and Production System

farming constitutes a *synergistic* process that is (a) a complete wastewater treatment technology and (b) a farming system that is capable of producing more high quality protein than soybeans on an equivalent land area (Ref 26)

A duckweed aquaculture treatment and production system can be organized as a series of plug flow channels as shown schematically in Figure 9 The amount of treatment surface area necessary to achieve an advanced quality treated effluent was about 1 6 m^2/PE (PE = person equivalent) in the pilot project in Bangladesh One unit of pond area for duckweed cultivation could support about double the area for fish cultivation, or approximately 3 2 m^2/PE The land area for levees and access pathways was about 1/3 of the total pond area, or another 1 6 m^2/PE, for a grand total of 6 4 m^2 of land needed per person (Ref 26) Average fresh duckweed production rates of 30 kg/m^2/year can sustain fish production rates between 1-1 5 kg/m^2/year, or about 1 6-2 4 kg/PE/year

The potential revenues to an owner/operator of a treatment and duckweed-fed fish production system in Bangladesh are attractive For example, at an average live weight price of fish of $1 5/kg, the gross revenues from duckweed-fed fish production in Bangladesh is on the order of $2 4-$3 6/PE/year, or about $0 38-$0 56/m^2/year in gross revenues from the total amount of land used for the treatment and production system These estimates exclude fees for service, the income from sales of reusable water, collateral crops grown on the containment and access portion of the land (about 1/3) and the excess duckweed meal not converted to fish Operating costs are primarily labor three agricultural laborers full time per hectare of duckweed production and one per hectare for fish production Wages in Bangladesh for casual agricultural labor are equivalent to about one kg of rice per day, worth approximately $1 00-$1 50

Duckweed aquaculture that does not include fish production to convert the duckweed produces dried duckweed meal as the final product The total amount of land needed for duckweed production in Bangladesh is 2 1 m^2/PE If duckweed meal is priced the same as soybean meal, between $0 25-$0 30/kg, gross revenues from duckweed meal sales will be about $0 38-$0 46/m^2/year of total land used, or about $0 80-$0 96/PE/year

The use of land for a duckweed post-treatment system is similar to a waste stabilization pond series The effluent quality from a duckweed aquaculture treatment system, in terms of the concentrations of oxygen consuming substances, suspended solids and nutrients, will be superior to a waste stabilization pond series of similar hydraulic retention time Adding fish production makes the package more extensive However, the duckweed aquaculture and fish production systems, are more intensive than terrestrial farming systems, such as rice, wheat or soybeans and the final product is high quality animal protein In Bangladesh, as in many developing countries, protein is in short supply, agricultural labor is abundant and there is an urgent need to intensify food production across the board

At the current stage of development of the duckweed aquaculture technology, there is not enough experience to conclude whether the effluent from a system with less than 20 days total retention time will meet the 1989 WHO biological quality guidelines for reuse in agriculture Where fish production is included in the integrated farm, discharging the final effluent from the duckweed system into the fish ponds can provide more than enough hydraulic retention time to meet the 20 day rule-of-thumb However, the biological quality of the treated effluent should not exceed 1 x 10^5 fecal coliforms per 100 ml to assure that the harvested fish are free of pathogenic organisms, bacteria and viruses (Ref 2)

The distinctive feature of a duckweed aquaculture and treatment system is its inclusion of integrated farming systems that can generate higher rates of return than conventional crops per unit of land Wastewater-fed duckweed aquaculture is especially competitive where (a) access to water is the main limiting factor for agriculture, (b) the cost of labor low and (c) protein is in short supply

3 37 LAND ISSUES

Land issues associated with wastewater treatment generally resolve to two main considerations the *amount* required and its *location* relative to the center of the urban area Ideally, the amount of land needed should be small, the price low, the distance short, the elevation difference negative and with no intervening obstacles In many countries the local governments own substantial amounts of reserve land that may be used for parks, solid waste disposal and wastewater treatment Increasing urbanization in most countries has generally made land in or near cities more expensive

Several factors may influence decisions to allocate land for wastewater treatment

- The owners of the urban land may have other, more financially attractive options,

- The current or projected unit price of the land may be considered too expensive to dedicate to the perceived "low value" wastewater treatment application,
- Aesthetic concerns about odors and appearance and their effect the value of adjacent land,

The location of the treatment plant is a key decision that will affect the capital and operating costs of the wastewater collection network and the treatment system While land is cheaper farther from the city, the savings can be quickly consumed by the higher capital and maintenance costs of the additional length of a trunk sewer that conveys the raw wastewater from the sewer system to the treatment plant

Anaerobic reactors are relatively compact They may be used to provide initial treatment, followed by pond, wetland or aquatic farming systems for post-treatment Together they represent a flexible configuration option that can reduce both land and infrastructure costs compared with pond-based systems alone The reactors can be located in or near the urban area in one or more locations Because anaerobic reactor effluent is virtually free of settlable solids it can be conveyed to the post-treatment site through a *small diameter effluent drainage* system designed as a *hydraulic* system, rather than as a sewer to convey raw wastewater

An infrastructure package consisting of anaerobic reactors connected to post-treatment facilities with solids-free effluent collection systems can have several important advantages (Ref 33)

- Reduced treatment and land requirements at the post-treatment facility, because major removal of solids and oxygen consuming substances takes place upstream of the post-treatment facility,
- Reduced construction costs of the effluent collector that replaces the trunk sewer because of shallower, narrower trenches, elimination of manholes and minimum requirements to control the gradient and horizontal alignment of the pipes,
- Reduced materials costs because smaller diameter pipes, running full, can handle the lower peak flows that result from attenuation of peak flows in the reactors, and
- Lower maintenance costs because blockages in the effluent conveyance system are less likely,

Anaerobic reactors and pond systems for post-treatment are both flexible with respect to scale and configuration A *subdivided* wastewater collection system can be considered with reactors distributed in multiple catchments connected by an effluent collection network A subdivided effluent collection system has potentially lower investment costs than a single sewer system because raw wastewater is conveyed shorter average distances Similarly, several post-treatment facilities could be distributed around the periphery of the urban area, increasing the options for planners to find less expensive land However, a major concern of a decentralization strategy would be *odor control at the reactor sites* with efficient gas collection and treatment in compost filters or the equivalent

Finally, commitment to a land intensive treatment technology near an urban area may be a good long term investment for the municipality

- When the 20-25 year working life of the treatment plant has been realized, the value of the land will likely have appreciated considerably because of the growth of the urban area,
- Development of the land for alternative uses will be low cost because the civil works associated with pond technologies are minimal and inexpensive to remove

IV FINANCIAL AND ECONOMIC ISSUES

4 1 GENERAL

Technologies for both wastewater collection and treatment in developing countries should be selected to protect public health and the environment, while ensuring the fullest use of the water resource The selection process should factor in the costs and availability of land, labor, equipment, and building materials and the cost, availability and reliability of support services, such as utilities, equipment and systems maintenance Technology selection objectives that should apply in most developing countries include

- technological simplicity,
- minimal capital and operating costs,
- maximum treatment and removal efficiency for capital and recurrent investment, and
- water reclamation and reuse capability to offset costs

4 2 COST AND COST COMPARISONS

Costs and cost comparisons are a complex set of issues and likely to be controversial at best Making comparisons that are accepted as valid generally is difficult because of the difficulty of obtaining data that are based on the same assumptions In addition cost information rapidly becomes obsolete

Nevertheless, treatment plant designs have become sufficiently standardized that developing lists of quantities of essential materials and equipment is relatively straightforward Recent similar projects can provide the basis for unit prices Within a particular country some site-specific variations may be expected, but comparisons with several recent projects in that country can provide important information about the economy of a new proposal More importantly, comparisons of capital and operating costs among alternative designs for a specific new site are essential if sound investment decisions are to be made For example, a comparative study conducted in Colombia in 1992 (Ref 34) concluded that the costs of anaerobic treatment plants (including post-treatment to secondary quality) for municipal wastewater appear to be between three to six times less than conventional aerobic alternatives, including activated sludge and extended aeration

By contrast, cross-country and cross-regional comparisons are difficult and may be misleading rather than useful For reasons too lengthy to present here, an activated sludge treatment plant in the Middle East may cost one third more than in Colombia, and three times as much as a similar one of equal capacity in the Indian Subcontinent

The capital and operating costs shown in Annex 4 are based on recently constructed plants or recently completed studies The analytical framework presented might be used to indicate the kinds of data required for a useful evaluation of proposed projects The single-sheet analytical approach presented was designed to facilitate sensitivity testing on uncertain economic values

The numbers in the boxes in the lower left quarter of each sheet are the "critical parameters and assumptions" that are intended to facilitate a process of pragmatic estimation If a particular number is uncertain or unknown, the analyst is encouraged to supply a plausible number based on the highest quality information available Sensitivity analysis often shows that the results are so insensitive to variations in a particular parameter (over the plausible range) that major research efforts to increase the level of precision of the estimate would be a waste of resources Where substantial sensitivity is found, guidance is given to the research or data collection effort

4 3 BENEFIT ESTIMATES

It is only recently, and as a result of increasing competition for investments funds, that efforts have been made to quantify the benefits of wastewater treatment Many of these have involved attempts to measure the costs associated with the transmission of waterborne disease and the savings that might result from improved wastewater treatment Because of the many factors that affect a community's health, however, most of these efforts have been disappointing There are several alternative approaches

As general concern with environmental quality has developed, the sophistication of *environmental impact evaluations* has increased substantially Many studies now routinely include assessments of the costs associated with repairing or mitigating environmental damage For example, if the discharge of X million cubic meters per year (MCM/year) of effluent of known quality will cost $Y million to clean up, a rough estimate of the treatment benefits, expressed as $/m^3, can be made for that particular treatment task

Also, there is the *lowest alternative cost* approach used widely in the recent past by the World Bank and similar agencies Although now in disuse, the method depends on the notion that the country in question has accepted that wastewater treatment to a specified quality standard is a social necessity If the last several wastewater treatment plants built are analyzed in terms of capacity and cost, and the result of the analysis produces values of unit treatment cost, it may be postulated that *expenditures to at least that level* represent an acceptable economic cost If a newly proposed plant, or one employing an alternative technology, can treat an effluent to the equivalent quality at a lower unit cost, the difference can be deemed to be the benefit of the new proposal

The indicative economic analysis in Annex 4 does not prescribe which method should be used to estimate the treatment benefit That there is such a benefit is certain otherwise societies would not demand that treatment facilities should continue to be built The specific value to be used in a particular case would be up to the project analyst Experienced engineers and economists working in that country would be able to make the estimates and could suggest where the process of sensitivity testing should start

Besides the basic treatment benefit, there are a variety of productive ways of reusing the treated effluent almost everywhere, but particularly in countries with water scarcity The unit *values added* for each of these uses are amenable to estimation The examples presented in Annex 4 assume that no wastewater is treated to potable quality Instead, an allocation has to be made between on-site use (which in these examples was an aquatic production system for duckweed and fish) and off-site uses, either in industry or irrigation

4 4 ECONOMIC AND FINANCIAL ANALYSIS

With appropriate site-specific input, the analytical format presented in Annex 4 will produce estimates of potential economic returns to investment in the construction of wastewater treatment facilities These estimates will be useful primarily to compare the conventional approach with possible alternatives The assumptions and estimates on which the analysis is based should be plausible and consistent, rather than precisely correct in an engineering or accounting sense

Financial returns are even more site specific, but they are easier to calculate because they must be based on legislated or agreed rates of payment Historically, sewer connection fees for wastewater collection have been levied by various levels of municipal government, and rates, often based on metered water use, are widely charged for collection and treatment services Rates, or tariffs, can be set to cover only operation and maintenance costs or O&M costs plus capital costs They may even be set sufficiently high to yield a previously established return on funds invested Because these rates are typically set at levels to cover costs, the question of financial "viability" simply does not arise

In developing countries grant financing of all forms of infrastructure development has declined Many governments have accumulated debt burdens of sufficient weight to make further borrowing imprudent or impossible As a result, new financing trends are emerging financing of public works by the private sector on a *build, own, operate* (BOO) or *build, own, operate, transfer* (BOOT) basis Consortia including contractors and bankers build a wide range of facilities ranging from airports to the British-French "Chunnel" Where revenue streams can be easily captured to pay for both construction and operation of these works, e g , landing fees for airports and tolls for highways, financing is normally straightforward The fact that the builders' own funds are used does, however, lead to an increased focus on economy of design

With respect to wastewater treatment the issues are less simple In many areas the costs of building sewerage networks and treatment facilities have escalated to the point that users have refused to be connected to the system Instead, wastewater is collected in cisterns and cess pits from which it is pumped out occasionally What does not seep into groundwater must be hauled away in tankers to a nearby treatment facility Frequently, a local stream is found to be a more convenient and inexpensive disposal alternative

Under these circumstances it is not possible to increase tariffs to cover the costs of building or operating new treatment facilities Alternative infrastructure that is less costly to operate becomes of interest to municipal decision makers, and the possibility of positive cash flows from a treatment plant becomes increasingly attractive The possibility of corporate profits induces engineers and contractors to seek out bankers Funds for construction come from non-traditional sources, and the attention of all participants is focused on less costly technologies It is here that on-site, productive uses of the wastewater resource, such as duckweed and fish production, are likely to play an important role in the future

4 5 INDICATIVE ANALYSIS

Although based on rough estimates, the analyses presented in Annex 4 indicate some interesting generalizations The costs of both construction and operation are far higher in Jordan than in Latin America or South Asia This may be because there is a continuing dependence on imported expertise and equipment

However, because the economy is relatively strong and water is so scarce, treating wastewater in Jordan can pay handsomely In fact, the potential economic value of recycled water is so high, especially for industrial reuse, that on-site uses will have to be tested very carefully before they can be broadly recommended This is particularly true for on on-site uses which are highly water consumptive, such as fish ponds

In more humid climates the greater general availability of water reduces the demand for, and the value of treated effluent for irrigation and the incentive for industries to accept water reclaimed from wastewater In this situation the profitability of effluent reuse on the site of the treatment facility may be considerably higher

4 6 MADRAS WASTEWATER RENOVATION

Shortly before the printing deadline for this document a paper became available that describes a large scale wastewater renovation project in Madras, the capital of the southern Indian State of Tamil Nadu The paper, prepared by the chairperson of the Madras Metropolitan Water Supply and Sewerage Board (MMSSB) and a World Bank Environmental Officer, illustrates the value of reuse of treated wastewater in a large urban area that faces chronic water shortages The paper was presented at the World Bank "Conference on Recycling Waste for Agriculture The Rural-Urban Connection", held in Washington 23-24 September, 1996 and is included in its entirety as Annex 5

Two industries, a petroleum refinery and a fertilizer plant, installed individual treatment plants at their own cost to treat a total of 30 MLD of secondary quality treated effluent supplied by the municipality to tertiary quality The treatment processes used are chemical treatment and sedimentation and reverse osmosis for polishing Reuse of the tertiary effluent replaces about 55 percent of the total water demand for the two industries that were previously dependent on groundwater of increasingly poor quality The results were twofold

1 The industries now have the capability to operate at about 75 percent of capacity in periods of severe drought For example, in 1987 industrial water supply was entirely shut down for six months because domestic water users were given priority

2 Thirty MLD of groundwater abstraction is replaced by the treated effluent

Each of the two industries financed the construction of its own tertiary treatment plant and relied on the municipality to manage the design and construction The capital cost of the two treatment tertiary plants was about $0 34 million per MLD of capacity The unit cost cited for effluent treatment from secondary to tertiary quality was Rs 40/kilolitre {sic} (1 kiloliter = 1,000 liters = 1 m^3), and the purchase price for secondary effluent was given as Rs 4/m^3 ($0 11/$m^3$) Although it is unclear in the paper, the municipality apparently charges Rs 4/m^3 for secondary treated effluent and Rs 25/m^3 ($0 70/$m^3$) for tertiary quality effluent (for users other than the two industries that built their own plants)

The example of mutually beneficial partnership between the public and private sectors has led to a commitment by another refinery to finance a 17 MLD tertiary treatment plant The municipal government plans to install an additional 100 MLD treatment plant by the year 2000 at an investment cost of about $163 million The plant will supply tertiary quality treated effluent at a price of Rs 30/m3 ($0 85/ m^3) to 14 medium and small scale industries that can not afford to finance their own individual treatment facilities The municipality expects to recover 85 percent of the costs of the treatment plant over thirty years

The Municipal government owns 780 ha of farm land that for several years was rented to farmers who grew fodder crops irrigated with secondary quality treated effluent Although the rental income covered operating costs, undesirable environmental side effects (groundwater contamination, odors and increased mosquito populations) led to collaboration with the Forestry Department in experiments with agroforestry, a more attractive, higher value effluent reuse option By the end of 1997 it is expected that 400-500 ha of woodlots will be irrigated with secondary treated effluent, and the return (approximately $560/ha/year) is estimated to be double that of fodder crops Another reuse option under consideration is irrigation of landscaped sites that have recreational and tourism value

Over-exploitation of groundwater in Madras, a coastal city, has led to saline intrusion into coastal aquifers and to deteriorating groundwater quality In addition to legislation to regulate groundwater use, consideration has been given to injection of treated wastewater into coastal aquifers to counter saline intrusion

advanced, or tertiary treatment	an added stage of biological, chemical and physical processes to treat wastewater beyond the secondary stage Removal of up to 99 percent of residual suspended solids and nutrients, the most important of which are nitrogen (N) and phosphorus (P)
aerobic treatment	biological conversion of organic material in wastewater to a more stable or mineral form by microbes in the presence of oxygen
ammonification	the anaerobic biodegradation of organic nitrogen to the reduced inorganic product, ammonia
anaerobic treatment	biological degradation of organic material in wastewater by bacteria in the absence of oxygen
attached growth	bacterial film that forms on a solid medium, such as particles, rocks or plastic netting
biogas	the gas mixture produced by anaerobic digestion of organic material, consisting of mostly methane (ranging from 60-95 percent depending on the composition of the wastewater), and carbon dioxide, ammonia, nitrogen gas and hydrogen sulfide
biomass	the mass of biological material in a system
BOD_5	biochemical demand, the quantity of oxygen in mg/l utilized in the biochemical oxidation of organic matter over a five day time period at standard temperature, a measure of the biodegradable organic matter in wastewater
clarifier	any large circular or rectangular sedimentation tank used to remove settlable solids from wastewater
COD	chemical oxygen demand, the quantity of oxygen in mg/l required for the chemical oxidation of carbonaceous (organic) material in wastewater using inorganic dichromate or permanganate salts as oxidants in a two hour test
coliform bacteria	a group of bacteria predominantly inhabiting intestines of humans and animals, used to indicate the presence of fecal contamination in water The group includes (a) all aerobic and facultative anaerobic Gram-negative, non-spore-forming, rod-shaped bacteria that ferment lactose with the production of gas, and (b) all bacteria that produce a dark purplish-green metallic sheen by the membrane filter technique used for coliform identification
colloidal matter	finely divided solids that will not settle, but may be removed by coagulation, biochemical action or membrane filtration
comminution	an in-stream process of grinding or shredding gross solids contained in wastewater
conditioning	the chemical, physical or biological treatment of sludges to improve their dewatering characteristics
denitrification	anaerobic reduction of nitrate by bacteria of the genus Nitrobacter to carbon dioxide and nitrogen gas (N_2)

enhanced primary treatment	an effluent quality intermediate between primary and secondary Depending on the composition of the raw wastewater, anaerobic reactors can achieve 65-85 percent removal of BOD_5 at 20° C (generally COD removal efficiency is 10-20 percent lower) and 60-80 percent SS removal
enteric disease	bacterial or viral infectious disease of the gastrointestinal tract, diarrhea or dysentery
eutrophication	nutrient enrichment of a lake or other surface water body, typically characterized by increased growth of planktonic algae and higher plants
facultative ponds	a treatment pond with an aerobic upper section and an anaerobic bottom section so that both aerobic and anaerobic biological process occur simultaneously
heterotrophic micro-organisms	bacteria and other microorganisms that utilize organic matter synthesized by other organisms for energy and growth
hydrolysis	initial stage of biochemical degradation that includes transformation of organic polymers (proteins, carbohydrates and fats) to organic monomers (amino acids, sugars and alcohols)
macrophyte	higher plant, a multicellular plant with a vascular system and diverse specialized structures
methane	a colorless, odorless, flammable, gaseous hydrocarbon, CH_4, present in natural gas, formed by the anaerobic decomposition of organic material
MLD	million liter per day
nitrification	the oxidation of ammonia to nitrate by the aerobic bacteria, Nitrosomonas, in the presence of atmospheric oxygen
NOD	nitrogenous oxygen demand, the amount of oxygen in mg/l needed for the biological oxidation of nitrogen, usually measured after the carbonaceous oxygen demand has been satisfied, also called "second stage oxygen demand"
nutrients	chemical substances that are necessary for all biological growth, usually refers to inorganic forms of nitrogen, phosphorus and potassium that can contribute to eutrophication of surface water bodies
organic loading	the amount of organic material, measured as COD or BOD_5, applied to a given treatment process, expressed as weight per unit of time per unit surface area or per unit weight
orthophosphate	a salt that contains phosphorus as (PO_4^{-3}), hydrolysis product of condensed (polymeric) phosphates, a nutrient required for plant growth
Parshall flume	a calibrated device for measuring the flow of liquid in an open conduit, consisting of a contracting length, a throat, and an expanding length At the throat is a sill over which the flow passes at Belanger's critical depth The upper and lower heads are each measured at a definite distance from the sill The lower head need not be measured unless the sill is submerged more than about 67 percent
pathogens	disease producing organisms, such as bacteria, viruses, helminths or protozoa transmitted through fecal-oral means and by wastewater
phytoplankton	algae, single-cell photosynthesizing plants

plug flow	flow in which fluid particles are discharges from a system in the same order that they entered the system, The particles retain their discrete identities and remain in the system for a time equal to the theoretical detention time
preliminary treatment	removal of large and heavy solids by screening and degritting,
primary treatment	sedimentation of 45-70 percent of settlable solids that contain significant amounts of oxygen consuming substances (20-40 percent), but little or no removal of colloidal and dissolved organic matter,
resource recovery	exploitation of wastewater as a source of (a) water for direct or indirect reuse (b) wastewater-borne nutrients (c) biogas fuel and (c) sludge as a soil conditioning ingredient
secondary treatment	removal of about 85 percent of suspended solids and BOD_5/COD and partial stabilization of the latter and some destruction of pathogenic organisms
sludge	the accumulated solids separated from wastewater during processing, the removed material resulting from chemical treatment, coagulation, flocculation, sedimentation, flotation and/or biological oxidation or anaerobic digestion of the organic matter in wastewater
splitter box	a division box that splits the incoming flow into two or more streams
sulfate reducing bacteria	bacteria capable of assimilating oxygen from sulfate compounds, reducing them to sulfides, important competitors of methane fermenting bacteria
suspended growth	a type of reactor in which the bacterial biomass is suspended in the bulk liquid and not attached to a solid medium (carrier), e g activated sludge or the UASB reactor
suspended solids	insoluble solids that either float on the surface of, or are in suspension in wastewater, solid organic or inorganic particles (colloidal, dispersed, coagulated, flocculated) physically held in suspension by agitation or flow, commonly abbreviated SS or TSS (total suspended solids)
thickening	the process after gravity sedimentation that increases the concentration of solids in sludges with or without the use of chemical flocculation
UASB	upflow anaerobic sludge blanket reactor, a type of high rate, suspended growth anaerobic reactor that maintains a suspended blanket of bacterial biomass
volatile solids	materials, generally organic, that can be driven off from a sample by heating, usually to 550° C for 60 minutes, commonly abbreviated VSS
waste stabilization ponds	a series of three to five ponds that may be used to treat wastewater at any stage of treatment, typically used to remove settlable solids and to stabilize organic material by anaerobic and aerobic microbial action and to remove pathogens by sedimentation and natural die-off

BOD_5	biochemical oxygen demand
BOO	build-own-operate
BOOT	build-own-operate-transfer
C	elemental carbon
°C	degrees Celsius (centigrade)
CH_4	methane gas
COD	chemical oxygen demand
cm	centimeter
CO_2	carbon dioxide
DO	dissolved oxygen
EPA	Environmental Protection Agency
g	gram
GLS separator	gas/liquid/solids separator in a UASB reactor
H	hydrogen
ha	hectare
H_2S	hydrogen sulfide gas
HRT	hydraulic retention time
IHE	International Institute for Hydraulic and Environmental Engineering
kg	kilogram
kW	kilowatt
kWh	kilowatt hour
m	meter
m^2	square meter
m^3	cubic meter
MMSSB	Madras Metropolitan Water Supply and Sewerage Board
MCM	million cubic meters per year
mg/l	milligrams per liter
MLD	million liters per day
mm	millimeter
ml	milliliter
N	elemental nitrogen
N_2	nitrogen gas
NH_3	ammonia
NH_4^+	ammonium ion
NOD	nitrogenous oxygen demand
NO_2	nitrite
NO_3	nitrate
O	elemental oxygen
O_2	oxygen gas
O&M	operation and maintenance
OM&R	Operation, Maintenance and Equipment Replacement
ortho-PO_4^{3}	orthophosphate ion
P	elemental phosphorus
PE	person equivalent
pH	symbol for the degree of acidity or alkalinity of a solution
S	elemental sulfur
SBR	sequencing batch reactor
SO_4	sulfate
SRT	solids retention time
SS	suspended solids
TKN	total Kjeldahl nitrogen, or total organic nitrogen
TSS	total suspended solids
UASB reactor	upflow anaerobic sludge blanket reactor
VFA	volatile fatty acids
VSS	volatile suspended solids
WHO	World Health Organization

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World Health Organization (WHO) Guidelines for Use of Wastewater in Agriculture and Aquaculture

The WHO guidelines for use of wastewater in agriculture and aquaculture were adopted in 1989 as a result of the consensus of a group of experts that met in 1985 in Engelberg, Switzerland The group examined the risks of wastewater reuse and ranked the *relative risks* of infection from microbes and parasites as follows

1 High with intestinal nematodes,
2 Moderate with bacterial infections and diarrheas,
3 Minimal with viral infections and diarrheas and hepatitis A, and
4 High to nonexistant with trematode and cestode infections, schistosomiasis, clonorchiasis and taeniasis, depending on local practices and circumstances

The microbiological quality guidelines recommended for wastewater use in agriculture are given below

Recommended Microbiological Quality Guidelines for Wastewater Use in Agriculture

Category	Reuse Conditions	Group Exposed	Intestinal Nematodes[a] (arithmetic mean of no eggs/liter[b])	Fecal coliforms (geometric mean of no per 100 ml[b]	Wastewater treatment expected to achieve required microbiological quality
A	Irrigation of crops likely to be eaten uncooked sports fields public parks[c]	workers consumers	≤ 1	≤ 1 000[c]	Series of stabilization ponds designed to achieve the microbiological quality indicated or equivalent treatment
B	Irrigation of cereal industrial and fodder crops pasture and trees[c]	workers	≤ 1	No standard recommended	Retention in stabilization ponds for 8 10 days for equivalent helminth and fecal coliform removal
C	Localized irrigation category B crops if worker and public exposure does not occur	None	N/A	N/A	Pretreatment is required by irrigation technology less than primary sediment

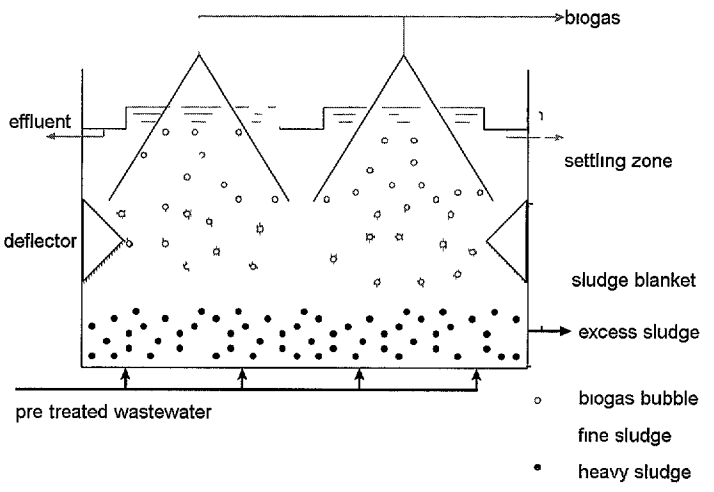
Source WHO (1989) Reuse of Wastewater in Agriculture A Guide for Planners Water and Sanitation Report 6 UNDP/World Bank Water and Sanitation Program 1990
Note In specific cases, local epidemiological, sociocultural and environmental factors should be taken into account and the guidelines modified accordingly
[a] *Ascaris* and *Trichurus* species and hookworms
[b] During the irrigation period
[c] A more stringent guideline (> 200 fecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact
[d] In the case of fruit trees, irrigation should cease two weeks before fruit is picked and no fruit should be picked off the ground Sprinkler irrigation should not be used

Technical Description and Design Parameters of

Loading and dimensioning parameters for UASB reactors were developed by Haskoning Consulting Engineers and Architects and described in a design manual, excerpts of which are given below

GENERAL

The first step in the design of a UASB reactor is to determine the volume of the reactor, upon which the details are based The most important details are influent distribution, gas/liquid/solids (GLS) separator and effluent collection Figure A is a schematic diagram illustrating the main elements of a UASB reactor 1 influent distribution, 2 sludge blanket, 3 gas dome, 4 effluent collection gutter



VOLUME

The volume of the reactor is determined by the *hydraulic loading, organic loading* or *gas loading* If COD is below about 1,000 mg/l hydraulic loadings are limiting and determine the volume Above 1,000 mg/l COD, the organic or gas loading should be applied as the design parameters Depending on the wastewater temperature and the hydraulic regime, a hydraulic retention time (HRT) is determined, usually between 3 and 6 hours for peak loading and 18 hours for average loadings

DEPTH

The typical water depth for a UASB reactor for municipal wastewater is 4 m Above that height a freeboard of 0 3-0 8 m is required A sump 0 3-0 5 m deep is required at the bottom of the reactor to allow complete drainage Four meters is considered the optimal water depth at the current state of the art Deeper, more compact designs will be the subject of further research

INFLUENT DISTRIBUTION

Even distribution of the influent over the bottom surface of the reactor is one of the essential points for good performance For municipal wastewater with high concentrations of suspended solids (SS) and fibrous materials, a series of splitter boxes has given the best results so far From each of the several outlets of the final splitter box, usually located on top or inside the upper part of the reactor, a pipe leads to a fixed point at the bottom of the reactor The density of distribution points should ideally be as high as possible, but for practical reasons, a density of one inlet point per 2 5-4 m^2 is regarded as optimal At the recommended densities, the inlet pipe can be 50-80 mm in diameter and the water velocity 0 3-0 8 m/s For example, a reactor with an effective volume of 1,000 m^3 (and a bottom surface area of 250 m^2) would have 40-62 inlet points

GAS/LIQUID/SOLIDS (GLS) SEPARATOR

The GLS separator is the second essential detail The inclination of the walls of the gas dome should be between 50-55° A flatter angle will lead to accumulation of sludge in the settling compartment and a steeper angle will result in an unnecessarily deep reactor The size of the opening between the digestion compartment and the upper settling compartment is determined by the aperture velocity The aperture velocity should be less than the initial settling velocity of the sludge Generally, less than 10 m/hour should be designed for at peak loading conditions and five m/h at average loading

conditions The overlap between the lower extremes of the GLS separator and the deflectors should be 10-20 cm (See Figure A) The surface area of the settler should be 60-80 percent of the total surface area of the reactor

EFFLUENT COLLECTION

Equal collection of the effluent is the third crucial part of the design of a UASB reactor Overflow wiers, or gutters, on both sides of the settling compartment provide good results The wiers should have 45° v-notches, rounded at the apex that provide an overflow table of 10-20 mm under all loading conditions

SLUDGE SAMPLING AND WITHDRAWAL

The dynamics of the sludge blanket can be controlled only by maintaining optimal blanket height To determine the height of the blanket and the distribution of the dry solids concentration over the height of the reactor, or the *sludge profile*, samples need to be taken at different heights Sampling ports of 25-40 mm diameter and located 20-30 cm apart are placed in the reactor wall More than one series of sampling ports are recommended for larger reactors Sludge withdrawal ports 100-150 mm diameter are placed at different heights and at different locations around the reactor Sludge should be withdrawn at 0 2, 0 5 and 1 5 m from the bottom, depending on the dynamics of the sludge blanket One set of sludge withdrawal pipes should be specified for each 100-150 m^2 of bottom surface area A sump with a 150-250 mm outlet is needed to completely empty the reactor

PERFORMANCE

Removal efficiencies depend on water temperature, hydraulic loading, reactor design, the quality of the works and the maintenance status of the reactor Depending on the composition of the wastewater, the removal efficiency of the UASB process may vary between 60-70 percent for COD and 75-85 percent for BOD_5, at influent temperatures between 20-35° At 24° C a properly designed and built reactor treating a typical municipal wastewater, when operated within the design parameters, may be expected to average removal efficiencies of 75 percent of BOD, 70 percent of COD and 80 percent of TSS Only negligible amounts of nitrogen and phosphorus are removed, 75-90 percent of N will be converted to *ammonium* ion (NH_4^+) Sulfur compounds are almost completely converted to *hydrogen sulfide* (H_2S) Removal of low concentrations of helminth ova is almost complete In endemic regions with high concentrations, 80-90 percent removal may be expected Removal of pathogenic bacteria and viruses is about 50 percent

The composition of biogas generated in the reactor depends on the characteristics of the wastewater and on the loadings applied Gas production is typically 220-250 l/kg of influent COD, excluding gas dissolved in the effluent For an influent COD concentration of 300 mg/l, gas production will be about 60-75 l/m^3 of treated wastewater The measured gas production is the primary control parameter of the reactor, e g , the parameter that indicates whether the reactor is functioning properly Lower production indicates inhibition of the biological process, sludge loss or some other problem Sludge production depends mainly on the concentration and organic content of suspended solids in the wastewater and the SRT and is adversely affected by sludge washout

CONSTRUCTION MATERIALS

For reasons of price and availability, concrete is the most utilized material for the tank and internal components of the reactor, such as columns, beams and GLS separator Steel or plastics for the tank are not price competitive, but internal components could be made of polyester or polyethylene if these materials are available at a competitive price The concrete must be of superior quality, well compacted, and cast in smooth forms Concrete exposed to a corrosive atmosphere, such as outlet structures, could be protected with a lining or coating of a corrosion resistant material, such as epoxy Larger splitter boxes are generally made of concrete and smaller ones of polyester Inlet pipes are preferably made of PE or PVC Other piping can be of PVC or polyethylene gas pipe (hostalene) The use of metal should be minimized, since the gas and the treated effluent are highly corrosive Where metal is essential, stainless steel should be used Galvanized surfaces may be used in non-submerged or open spaces, such as ladders and railings

ODOR ABATEMENT

Gases from anaerobic treatment plants contains many offensive compounds If odors cause a problem they may be reduced by ensuring a gas-tight gas collection system Concrete gas collectors may be lined Settlers and effluent gutters can be covered and the air above the water surface extracted and treated by compost filtration or a similar process

I INTRODUCTION

The design of the four wastewater treatment plants selected for this review and visited by the authors derive from practical experience in an initial research project in Cali, Colombia that studied anaerobic wastewater treatment between 1983-1988 Financing for the research project was provided by the Dutch government, and technical assistance to the Cali municipality was supplied by Haskoning Consulting Engineers, the Agricultural University of Wageningen and the University del Valle (Ref 22, 23) Practical experience gained with the Cali pilot plant (0 064 MLD) led to the design and construction in 1990 of a full scale treatment plant, (4 MLD) serving a population of about 20,000 in Cali and to the larger 32 MLD Rio Frio treatment plant in Bucaramanga, commissioned in 1991 and expanded to 42 MLD peak capacity in 1994 (Ref 17, 22, 23)

At about the same time the Dutch government provided technical assistance to the government of India in an integrated environmental and sanitary engineering project to prevent pollution of the Ganges River Basin, The Ganga Action Plan Again Haskoning Consulting Engineers were the source of technical assistance In 1989 Haskoning and their Indian collaborators, Iram Consult, designed a full scale (5 MLD) UASB treatment plant that was built in Kanpur in the state of Uttar Pradesh to demonstrate the feasibility of anaerobic treatment in India The experience gained treating municipal wastewater in the Kanpur demonstration project led to the construction of a 14 MLD municipal wastewater treatment plant in Mirzapur, also in Uttar Pradesh Later, a 36 MLD plant was built in Kanpur to treat a mixture of tannery wastewater and municipal wastewater (Ref 17) As of 1996, over 300 MLD of UASB treatment capacity, in thirteen treatment plants, is being installed in Northern India (Ref 21)

Each anaerobic treatment plant consists of the following main elements, illustrated in Figure B

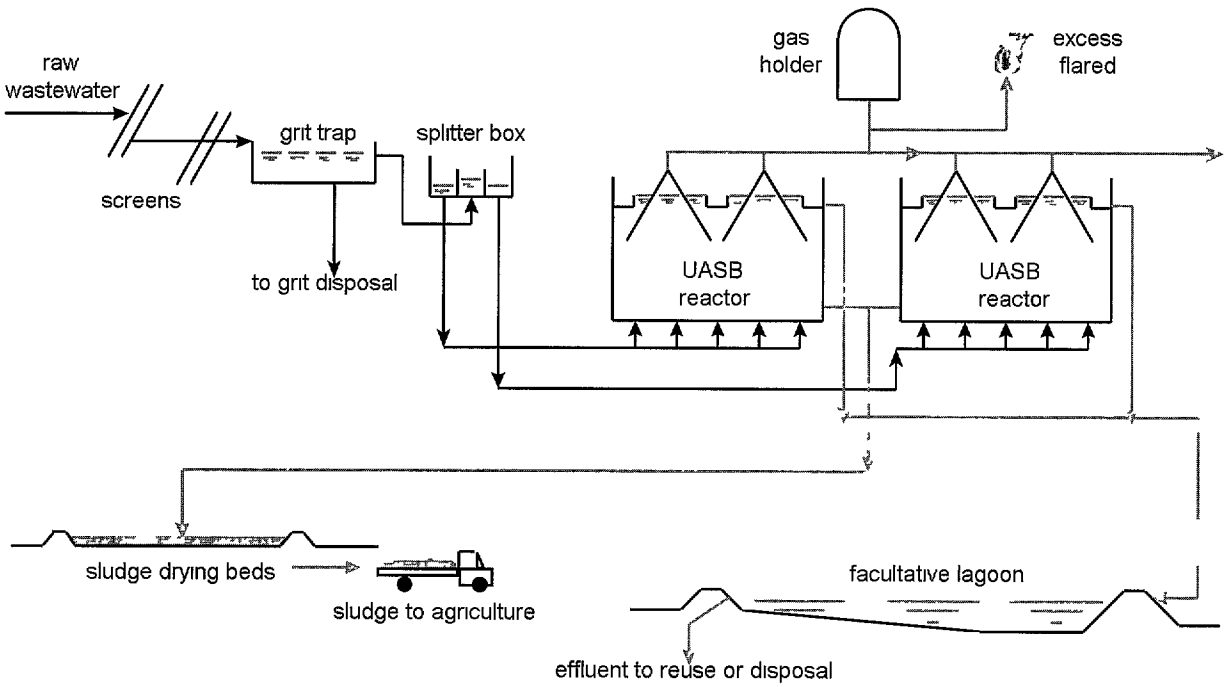


Figure B Flow Diagram of a UASB Treatment Plant

- overflow bypass and flow measurement structures
  1 preliminary treatment structures
  2 coarse and fine screens
  3 grit trap
  4 enhanced primary treatment structures (UASB reactor modules)
- byproduct handling structures
  1 gas handling system
  2 sludge drying beds
- post-treatment structures
  1 all three municipal wastewater treatment plants use facultative lagoons,
  2 flash aeration, mechanical aeration for 1/2 hour, and chemical flocculation (only at Kanpur 36 MLD mixed effluent treatment plant)

The basic operating parameters of the UASB unit process for treatment of municipal wastewater, such as upflow velocity (0 5-1 0 m/s), flow distribution (0 25 inlet/m^2) and average hydraulic retention time (HRT 4-6 hours) were established empirically in the early applied research project in Colombia Operating experience provided some practical improvements to the design that made the plant more reliable and easier to maintain For example, it was established that *thorough preliminary treatment is essential* to prevent large solid particles from entering the reactors, where it will tend to clog the flow inlets and decrease the effective volume Baffles installed in front of the effluent discharge gutters were found to be effective in avoiding obstruction of the v-notches The corrosiveness of the effluent required substitution of stainless steel or plastic for metal components and protective coating of concrete surfaces

Table A gives the average removal efficiencies the UASB anaerobic treatment for oxygen consuming substances (BOD_5 and COD) and total solids for the four treatment plants visited, including three treating municipal wastewater at Bucaramanga, Colombia, Mirzapur and Kanpur in India and one treating a mixture of tannery and municipal wastewater effluents, also in Kanpur

II KANPUR 5 MLD DEMONSTRATION TREATMENT PLANT

2 1 BACKGROUND

The Kanpur 5 MLD demonstration project was part of the larger Indo-Dutch Environmental and Sanitary Engineering Project at Kanpur and Mirzapur in the state of Uttar Pradesh This state-level project was part of an integrated program of prevention of pollution to the Ganges Basin in cooperation with the Ministry of Environment and Forestry of the Government of India

The treatment plant was built with the following objectives in mind

- to demonstrate the feasibility of anaerobic treatment of wastewater under typical conditions in India,

Table A
Comparison of Average Influent and Reactor Effluent Quality and Removal Rates
From Four Full Scale UASB Reactors

Parameter		Municipal Wastewater			Mixed
		Bucaramanga, Colombia	Mirzapur, India	Kanpur, India	Kanpur, India
Design Peak Capacity	(MLD)	42	14	5	36
Operating Capacity	(MLD)	36	10	4 8	21 8
Average organic loading					
COD	(mg/l)	400	360	560	1,183
BOD_5	(mg/l)	150	180	210	484
TSS	(mg/l)	230	360	420	1,000
Average Removal Efficiency					
COD	(%)	65	61	74	57
BOD_5	(%)	75	66	75	63
TSS	(%)	70	70	75	56
Average HRT	(hour)	5	8	6	5 2
Influent temp Range	(°C)	23-25	21-30	20-30	22-30
Gas production	(m^3/day)	3,300	500	480	

- to gain practical experience with the design variables to facilitate extension of the technology in Kanpur and Mirzapur,
- to assess treatment efficiencies,
- to develop an operations and maintenance manual, and
- training of the plant's personnel in operation and maintenance of a UASB treatment plant

2 2 PLANT LAYOUT

The 5 MLD treatment plant was designed to account for the differences in conditions between Colombia and India more concentrated wastewater, different composition, wide fluctuation between summer and winter temperature The plant was designed to accommodate different loading rates and to be able to studv design alternatives The UASB reactor was designed with a 1,200 m^3 total volume divided among three compartments, one with 600 m^3 and two with 300 m^3, and with the capability to alter the flow rate to each of the compartments

The raw wastewater from a pumping station is received by a flow control box From the flow control box the raw effluent flows by gravity into the grit trap that prevents heavy particles from entering the reactor From the grit trap the effluent flows to the splitter box where the flow is divided among the three compartments Distribution boxes receive the flow from the splitter box and distribute the effluent evenly to the feed inlet pipes at the bottom of the reactor compartment

The volume of the raw influent is measured in a Parshall flume The biogas is measured by a wet-test gas meter for each chamber Sludge may be discharged by gravity into sludge pits (sumps), where it is pumped to the sludge drying beds

The 600 m^3 first compartment was used as a reference unit Compartments 1 and 3 had no baffles to prevent floating material from clogging the v-notches in the effluent collection gutters All compartments are 4 5 meters deep Compartment 2 has baffles in front of the effluent collection gutters, while compartment 3 has double the number of feed inlets (0 5/m^3)

2 3 DESIGN CRITERIA FOR THE KANPUR 5 MLD PLANT

- Twelve MLD capacity inlet to treatment plant
- Flow control structure to regulate the feed rate of approximately 5 MLD
- Two grit traps that operate in tandem, each with 250 m^3 capacity, horizontal velocity 0 3 m/s, surface loading 45 m/h, and grit storage capacity of three days
- Flow division box with four-part division of 125 m^3/hour each
- Three-compartment UASB reactor, consisting of 600 m^3, 300 m^3, 300 m^3 volume compartments with the following characteristics
  - a) average HRT of 6 hours,
  - b) minimum HRT 2 4 hours,
  - c) organic loading rate 2-5 kg of COD per m^3 of reactor volume per day,
  - d) reactor depth 4 5 m,
  - e) feed inlet density one per 3 7 m^2, except for compartment 3 (one per 1 85 m^2),
  - f) aperture between gas collectors 0 3 m,
  - g) average flow velocity in aperture 4 m,
  - h) overlap baffles at gas collectors 0 15 m,
  - i) average wier loading at effluent gutters 0 7 m^3/m/hour
- Sludge drying beds to handle sludge production as follows
  - j) sludge production 300 mg/liter of total solids,
  - k) sludge concentration 6 percent total solids,
  - l) wet sludge production 25 m^3/day,
  - m) sludge loading on drying beds 265 kg/m^2/year of total solids,
  - n) height of sludge application 0 2 m,
  - o) duration of drying cycle and removal 14 days
- Gas system to handle maximum gas production of 20 m^3/hour, with one gas meter per compartment with maximum gas capacity of 10 m^3

2 4 RESULTS OF DEMONSTRATION PROJECT

2 41 PROCESS PARAMETERS

The plant was started up at an HRT (hydraulic retention time) of six hours and without addition of seed sludge After six weeks, the inflow was stopped and the sludge was allowed to digest for a period of two weeks Within one month after restart, the plant was considered to be operating satisfactorily The influent temperature ranged between 20-30° C

The best performance was obtained in compartment two where the effluent gutters were provided with side baffles Performance was five percent

less in the other two compartments without baffles No difference in performance was noted in the compartment with double the recommended feed inlet density However, during startup, compartment two filled up more rapidly with sludge and had a slightly faster startup time

COD and TSS removal efficiencies were higher than in previous research experience, but the BOD_5 removal rate was lower because of the septic nature of the effluent and the presence of *sulfates* in the influent to the plant that tends to retard the growth of methanogenic bacteria The source of the sulfate is chromium sulfate, used by tanneries Effluent discharge standards to surface water in India are BOD_5 30 mg/l, TSS 50 mg/l Post-treatment is necessary to meet treatment objectives Average removal efficiencies of the Kanpur 5 MLD reactor are presented in Table B

The lower influent temperature (20° C) in winter does not affect the treatment efficiencies appreciably, but lower sludge activity reduces gas production during a three week period The gas is discharged into the atmosphere through a stack No odor problems from gas disposal were noticed at the reactor site, and there were no reported complaints from neighbors The most likely explanation is that the odors from the treatment plant are not considered unusual Urban areas in India typically have open drains, and the odors from the drains are an unavoidable fact of urban life If odor control measures become necessary, covering all exposed water surfaces, extracting and treating the gases in a compost filter would reduce odors at the plant site to negligible levels

2 42 CONSTRUCTION DETAILS

The gas collection domes were constructed of concrete, but poor workmanship resulted in porosity and leakage of gas that grouting could not completely correct The design of the gas domes was changed completely to *fiber reinforced plastic* (FRP) sections attached to a concrete structure The FRP sections can be removed to provide access to the water surface inside the gas collection dome

The feed inlet pipes were made of *polyethylene* (PE) pipes joined by welding Obstructions can result from careless welding that can cause frequent clogging of the inlet pipes The system has been changed for the Mirzapur UASB reactor design

Poor quality casting of the reactor walls led to the decision to use masonry walls for the Mirzapur reactors Masonry walls can be plastered with sulfide resistant cement and covered with an epoxy coating Masonry is also more resistant to CO_2 corrosion than concrete The original effluent gutters were made of coated steel, but were completely corroded within two years Stainless steel was rejected as a replacement material, and FRP was selected for the Mirzapur design

III MIRZAPUR 14 MLD TREATMENT PLANT

3 1 BACKGROUND

The city of Mirzapur has a population of about 130,000 Municipal wastewater was previously discharged directly into the Ganges River through four large natural drains, called *nallahs* The Indo-Dutch Environmental and Sanitary Engineering Project constructed infrastructure to intercept the wastewater in the *nallahs* and pump it to the treatment plant, The plant consists of advanced primary treatment in UASB reactors and post-treatment in a facultative lagoon with retention time of one day The current flow into the treatment plant is about 10 MLD and is projected to increase to 14 MLD by the year 2006 and about 20 MLD by 2021 The construction plan called for a 14 MLD peak capacity plant with expansion capability to add reactor modules and pond space to reach the 20 MLD planning horizon

3 2 DESCRIPTION OF TREATMENT PLANT

The layout of the Mirzapur UASB treatment is as shown in Figure B The inlet chamber receives raw

Table B
Kanpur 5 MLD Average Influent and Effluent Quality and Removal Rates

Parameter (averages)	Influent (mg/l)	Effluent (mg/l)	Removal Rate (%)
COD	560	150	74
BOD_5	210	55	75
TSS	420	110	75

Compartment two

wastewater through a 700 mm diameter main from a pumping station Two parallel grit traps operate in tandem on a two day cycle of manual cleaning The surface loading rate of the grit traps is 45 m/h The UASB reactor is comprised of two 2,400 m^3 units, designed for an organic loading rate for COD as *volatile solids* of 0 3 kg/day/m^3 of reactor capacity The minimum height of the sludge blanket is two meters, and the average HRT is about eight hours The sludge settling compartment of the GLS (gas/liquid/solids) phase separator is designed to accommodate a maximum surface loading rate of 2 m^3/m^2/hour

Gas production is on the order of 500 m^3/day on the basis of a gas yield of 0 1-0 15 m^3/kg of COD removed The gas composition is about 80 percent methane and has a potential to produce 70 kW of electric power Because the daily power requirement of the plant is 12 kW, two dual-fuel generator sets of 18 kW are provided Until other applications can be developed, the excess gas will be flared

Excess anaerobic sludge (the amount in excess of that needed to sustain anaerobic digestion) is produced at the rate of 0 2 kg of total suspended solids (TSS) per m^3 of treated effluent and is withdrawn regularly and dewatered on sludge drying beds that have a total area of 2,000 m^2 The loading rate on the drying beds is 520 kg/m^2 of total solids per year, with a drying time of seven days The dried sludge is removed manually and sold to farmers as a soil conditioner

3 3 UASB PERFORMANCE

Table C presents average removal rates and the average quality of the influent, reactor effluent and final effluent (Ref 15)

IV KANPUR 36 MLD MIXED EFFLUENT TREATMENT PLANT

4 1 GENERAL

The 36 MLD treatment plant was built to treat a mixture of municipal wastewater and the effluent from about 175 tanneries in Kanpur The project was part of the Indo-Dutch Environmental and Sanitary Engineering Project assistance to the Ganga Action Plan of the Ministry of Environment and Forestry The UASB reactor design was based on about five years practical experience by the consultants with the smaller Kanpur 5 MLD treatment plant adjacent to the new 36 MLD plant and on the results of earlier research in Colombia conducted by the same consultants

4 2 TANNERY WASTEWATER

The projected flow of tannery wastewater by 2001 is about 9 MLD, plus about 2 6 MLD of domestic wastewater that will be collected in the same system, for a total of 11 6 MLD The average quality of the wastewater is approximately 3,000 mg/l of COD, 1,250 mg/l of BOD_5, 1,500 mg/l of TSS and 800 mg/l of sulfate Each tannery operates its own preliminary treatment plant that consists of screening, grit removal and sedimentation The pre-treated tannery effluents are discharged into a 10 8 km system of lined channels that collects effluent from all four clusters of tanneries, each with a pumping station Each pumping station has two screens and grit traps

Chromium sulfate is the main chemical reagent for the "chrome tanning" process As a first order improvement, the tanneries are taking measures to increase the efficiency of chrome fixing in the leather Second they are being encouraged to invest in direct or indirect recycling techniques

From 50-80 percent chromium recovery is possible with direct recycle of used chrome liquors to the tanning and "pickling" processes and more efficient collection systems Finally chromium salts can be chemically precipitated and recovered for reuse According to project authorities, the price of chromium sulfate from the supplier is Rs 41/kg (about $1 15) The recovered reagent costs about Rs 14/kg ($0 39), and the cost of investment in the recovery system be recouped within one year

4 3 MUNICIPAL WASTEWATER

A conventional aerobic treatment facility with a capacity of 130 MLD is being constructed adjacent

Table C
Mirzapur 14 MLD Average Influent and Effluent Quality and Removal Rates

Parameter (averages)	Influent (mg/l)	Effluent (mg/l)	Removal Rates (%) Reactor Effluent	Final Effluent
COD	411	160	61	81
BOD_5	193	50	66	84
TSS	360	108	70	87

to the 36 MLD anaerobic treatment plant The aerobic treatment plant was planned before the experience with the anaerobic treatment technology was available for consideration Current plans are to provide final treatment of the anaerobic reactor effluent in the aerobic facility Of the 160 MLD of total municipal wastewater, 25 MLD will be used to dilute the tannery wastewater 3 1 to reduce the sulfate concentration to a treatable level The quality of the municipal wastewater is classified as medium strength with concentrations of COD of 500-574 mg/l, BOD_5 200-240 mg/l, TSS 450-240 mg/l and sulfates 110-150 mg/l

4 4 PRELIMINARY TREATMENT

The layout of the treatment plant is as shown in Figure B, except that equalization tanks are provided upstream of the reactors The influent passes through mechanically raked, coarse rectangular bar screens with 15 mm clearance, and set at an angle of 70° Mesh screens are placed behind the bar screens to remove finer material Screened material is collected on a conveyor belt that transports the debris to a container Stainless steel mesh sieves with 12 x 12 mm apertures are set at a 60° angle with respect to the grit chamber floor and are designed to be cleaned manually Two pairs of grit channels are operated in tandem on an alternate day cleaning cycle, one pair for the tannery wastewater and the other for municipal wastewater The dimensions for the grit channel for tannery wastewater are 22 11 x 2 0 x 0 7 m, and for the municipal wastewater 14 44 x 1 5 x 0 63 m

4 5 WASTEWATER EQUALIZATION, INTERMEDIATE PUMPING AND MIXING

Gravity flow supplies tannery wastewater to two equalization tanks where it is mixed with municipal wastewater that is pumped in to achieve a constant dilution ratio The volume of each is 3,300 m^3 of municipal effluent plus 5,400 m^3 of tannery effluent, for a total of 8,700 m^3 of mixed effluent The two tanks are 4 m deep by 37 2 m in diameter and have submersible mixers

4 6 UASB REACTORS

The two reactor modules are each 38 9 x 20 8 x 6 2 m in size and are built above ground The influent is pumped from the mixing tank to the reactors at a constant rate and the effluent flows by gravity to the post-treatment plant The average HRT is 5 3 hours and the pH inside the reactors is kept somewhat high (7 4-7 5) to reduce sulfide toxicity The reactors reached full performance in October 1994

Table D summarizes average performance of the UASB reactors

4 7 DISCUSSION

The contribution of volatile fatty acids (biologically degradable soluble components) to the residual COD in the effluent is low, indicating that the biological performance of the reactor is high The majority of the residual COD in the effluent consists of suspended solids, indicating that efforts toward optimization should be directed toward removing solids

4 8 POST-TREATMENT

The post-treatment technology selected for the mixed effluent treatment plant was *flash aeration,* to strip dissolved gases The detention time for aeration is 30 minutes, followed by chemical flocculation to remove suspended solids The treatment plant is intended for startup by the end of 1996 Final treatment of the effluent will be provided by the adjacent aerobic treatment plant when it is eventually completed

V 42 MLD UASB TREATMENT PLANT IN BUCARAMANGA, COLOMBIA

5 1 BACKGROUND

The "Rio Frio" municipal wastewater treatment plant located in Bucaramanga, Colombia, was developed in the context of a master environmental sanitation plan for the Bucaramanga metropolitan area that included a reforestation program The agency responsible for the master plan is *CDMB,* the Spanish acronym for *Autonomous Corporation for the Defense of the Plateau of Bucaramanga,* organized in 1965 to counter catastrophic erosion on the plateau where the city, now almost one million population, is located

The original proposal for long term wastewater treatment capability was waste stabilization ponds that would ultimately occupy a total of 42 ha The anaerobic enhanced primary treatment in UASB reactors and post-treatment in ponds reduced the land requirement for the plant to 20 ha for the 2008 planning horizon

The Dutch government provided assistance to CDMB between 1983-1988 to implement the master plan, and the experience with the UASB research project in Cali led CDMB to decide to test the UASB reactor and several other options on a pilot scale

Table D
Kanpur 36 MLD Average Influent and Effluent Quality and Removal Rates

Parameter	Unit	Influent	Effluent Reactor 1	Effluent Reactor 2
Total flow	m^3/day		11,248	10,520
Temperature	^{o} C	26	26	26
pH		8 3	7 4	7 5
COD_{total}	mg/l	1,183	504	517
$COD_{filtered}$	mg/l	506	246	252
$BOD_{5\ total}$	mg/l	484	187	190
$BOD_{5\ filtered}$	mg/l	211	97	95
VFA	meq/l	3 9	1 0	1 0
Alkalinity	mg/l	18 4	22 1	22 0
TSS	mg/l	1,000	452	459
VSS	mg/l	480	198	202
Sulfate	mg/l	396	193	209
Sulfide	mg/l	84	139	137
TS	mg/l	4,632	2,456	2,569
VS	mg/l	852	329	344
Average Removal Efficiency				
COD	%		57 9	56 9
BOD_5	%		63 5	62 2
TSS	%		56 4	56 2

The CDMB engineers designed the plant with technical assistance from the Dutch team The components and layout of the Rio Frio UASB treatment plant are as shown schematically in Figure B

The first two reactor modules and a post-treatment lagoon were completed during the construction phase 1990-1991 and were fully operational in July 1991 The cost of building the plant was $2 5 million, excluding the cost of land, or $17 per caput Annual operating costs are about $101,000 ($0 43/caput or $0 008/$m^3$) A breakdown of the investments is shown graphically in Figure C, and the 1991 annual operating costs are analyzed in Figure D The third reactor module and the second facultative lagoon were completed 1994 and the third reactor module started up in December 1994

The performance of the UASB plant as been satisfactory Over the five year period the final treated effluent quality showed an average BOD_5 removal of 90 percent, of which 75 percent is removed in the reactors Table E gives influent and effluent quantities and qualities and removal efficiencies at various stages in the treatment process

The main problems have been construction imperfections, temporary under-capacity caused by phased implementation of the works, and complaints about odors from land owners who want to develop housing near the plant CDMB has responded by covering the exposed water surfaces above the UASB and extracting the gases The extracted gases are then exhausted through a compost filter to remove odors The biogas generated by the plant is flared in the absence of any useful application thus far

The factors that accounted for the success of the project include,

- CDMB's autonomy, technical and managerial competence and financial stability
- CDMB's institutional culture that encourages innovation and risk taking
- The availability of sound technical assistance and the ability to take advantage of it
- Competent contractors willing to experiment with unfamiliar building materials
- Adequate supervisory and financial resources to manage the plant

Management of the Rio Frio plant is likely to be sustainable CDMB has taken action to correct the odor problem and corrosion on the metal and concrete components of the plant, along with leaks in the

gas collection system and inappropriate screens It is likely that CDMB will be able to build the two additional treatment plants called for in the master plan and will be able to manage them successfully

5 2 DESIGN PARAMETERS OF THE RIO FRIO UASB TREATMENT PLANT

Influent Characteristics

		average	minimum	maximum
Average flow (MLD)		37	-	42
Temperature (° C)		24	23	25
COD	(mg/l)	380	330	450
BOD_5	(mg/l)	160	105	180
TSS	(mg/l)	240	210	300
$N_{Kjeldahl}$	(mg/l)	29	24	35

UASB Reactors	**units**	
$HRT_{average}$	(hour)	5 2
$HRT_{minimum}$	(hour)	3 5
number of reactors	(units)	3
volume of each reactor	(m^3)	3350
water depth of reactor	(m)	4
influent distribution	(inlet)	288, one per 2 9 m^2, distribution via 3 splitter boxes
GLS separator	(units)	18, dimensions 2 4 x 19 2 m, inclination 52°26′
velocity in settler aperture	(m/hr)	4
sludge withdrawal	(outlet)	3 at 1 5 m from bottom, 1 at 0 5 m from bottom, diameter 100 mm

Facultative Ponds

BOD_5 (organic) load from reactors	(kg/day)	1,400
design organic loading rate	(kg/ha/day)	2 7
size	(hectare)	dimensions 135 x 200 m, with 3 horizontal baffles 45 x 200 m
depth	(m)	2 for first channel, rest 1 5
dredging of sludge		once every 8-10 months
detention time	(hours)	24

Sludge Drying Bed

total area	(m^2)	5,760
number of units		48
size per unit	(m^2)	120 (6 x 20 m)
sludge loading depth	(m)	0 25 to 0 3
drying time	(day)	7
dry solids product	(%)	> 50

Gas Production

measured production	(m^3)	1,100/reactor, or 71/1,000 m^3 of treated wastewater
composition	(%)	methane (CH_4) 80, carbon dioxide (CO_2) 10, nitrogen (N_2) 10, hydrogen sulfide (H_2S) 0 1

Table E
Average Influent and Effluent Quality and Removal Rates, Including Post-treatment for Bucaramanga 42 MLD Treatment Plant

Parameter	Unit	Influent	UASB	Lagoon	Total
Total flow	MLD	42	15 3	30 6	46
HRT	hour	-	5	30	-
COD_{total}	mg/l	400	160	95	95
$COD_{filtered}$	mg/l	180	93	82	82
$BOD_{5\ total}$	mg/l	150	35	19	19
$BOD_{5\ filtered}$	mg/l	70	20	15	15
TSS	mg/l	230	85	22	22
VSS	mg/l	155	40	18	18
Removal Efficiencies	%				
COD_{total}	%	-	65	40	75
$BOD_{5\ total}$	%	-	75	50	90
TSS	%	-	70	75	90

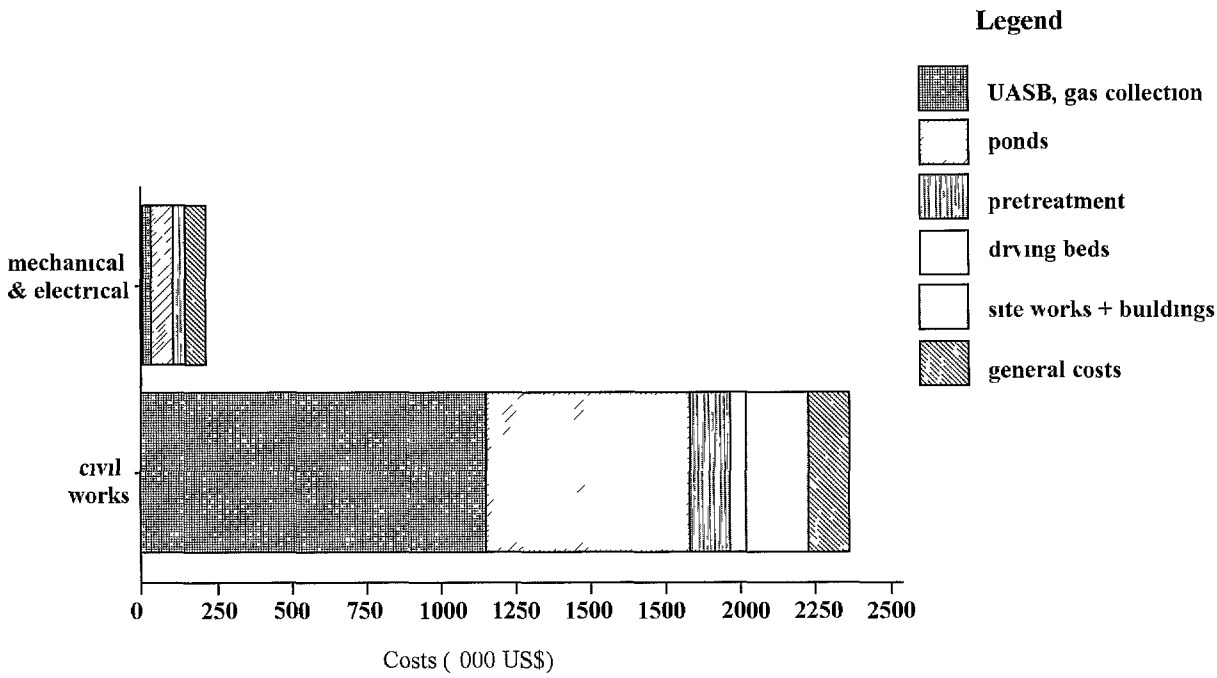


Figure C Breakdown of Investment Costs for Bucaramanga Anaerobic Treatment Plant

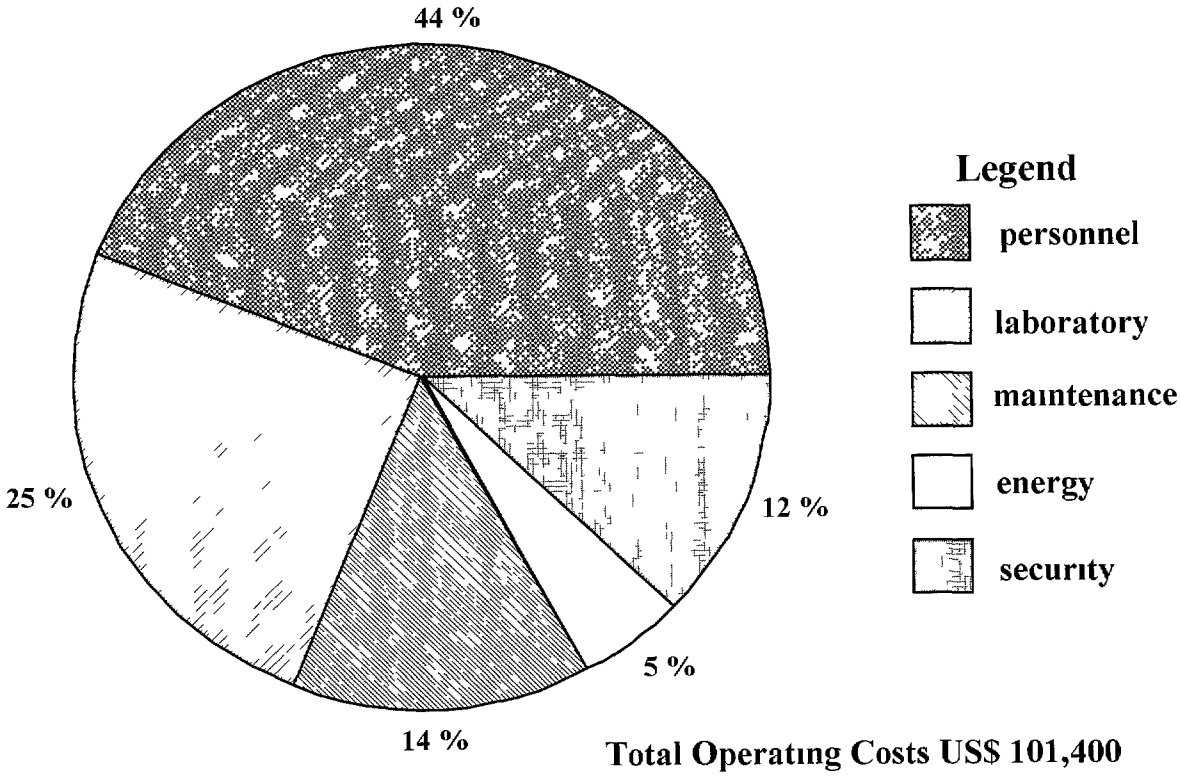


Figure D Breakdown of Operating Costs for Bucaramanga Anaerobic Treatment Plant

INDICATIVE ECONOMIC ANALYSIS OF WASTEWATER TREATMENT

1 INDICATIVE ANALYSIS

Table A summarizes the results of the indicative economic analyses presented in six scenarios Each scenario is described in detail by a single worksheet which follows Table A Three climatic zones were selected as examples arid sub-tropical, humid tropical and very humid and the specific examples from each were Jordan, Colombia and Bangladesh respectively The dominant independent variable in these examples is the availability of water, which affects the value of water in that country

Economic analysis is an attempt to decide how best to allocate resources to development activities based on the full costs, direct and indirect to achieve a set of benefits, also direct and indirect Financial costs and benefits are the easiest to identify and estimate and are included in the set of economic costs and benefits Economic costs and benefits are less easily quantified, particularly when they are indirect and materialize over the long term

The values of the critical parameters and assumptions were based on rough estimates and the best information about specific projects available from each country Readers are encouraged to supply assumptions that refer to a context of their choosing and to examine the economic costs and benefits of particular projects of interest to them

2 COSTS

- The discount rate represents the assumed cost of capital and affects the outcome of the project Three outcomes are analyzed, based on three discount rates 8, 10 and 12 percent
- Capital outlay is the total direct investment cost of building the treatment plant
- Operation, Maintenance and Equipment Replacement (OM&R) represent the costs of maintenance of the facility and periodic replacement of equipment
- Value of water used on site is the term representing the amount of water used in the treatment process itself that is not available for reuse, i e , not available to sell
- Energy produced on site is an estimate of the value of biogas fuel produced, if any
- Sludge disposal costs are estimated separately from O&M costs to illustrate the differences in sludge handling costs between anaerobic and aerobic treatment plants
- Total costs are the sum of the costs listed above and are used to determine the annual economic cash flows that are the basis for calculating the economic rate of return for the investment

3 BENEFITS

- The treatment benefit is an estimate of the value of the environmental damage avoided or mitigated by treating the wastewater
- Value of use on site represents an estimate of the value of the agricultural production on site that is made possible by the reclaimed wastewater, including duckweed meal production, collateral crops, such as vegetables, and fish
- Value added in industry is the term to estimate the value of the incremental production that is made possible by the availability of the treated effluent to the industry
- Value added in reuse for irrigation is an estimate of the incremental production off-site that is made possible by the use of the treated effluent to farmers
- Total benefits is the sum of the benefits listed above

4 OUTCOMES

- Net economic cash flow represents the difference between the total costs and total benefits
- The economic internal rate of return calculates the economic rate of return on investment in wastewater treatment based on a series of annualized cash flows that accrue from the sum of the annual benefits of treatment on-site use, reuse for irrigation and value-added in industry

5 COST INDICATORS

- Unit gross treatment cost indicates the total economic costs of treatment of one cubic meter of the wastewater described by the critical parameters and assumptions

- Unit net treatment benefits is the term that indicates the net gain to the society of treatment of one cubic meter of the wastewater described by the critical parameters and assumptions

- Unit cost of BOD and COD reduction are similar to the unit gross treatment cost, except that the unit of interest the cost of removing one kg of BOD or COD, both measures of oxygen consuming substances

Table A
Comparisons of Results of Indicative Analysis for Activated Sludge Treatment Plants and Resource Recovery Treatment and Production Systems

		ARID e g , Jordan		HUMID e g, Colombia		VERY HUMID Bangladesh	
	Scenario	1A	1B	2A	2B	3A	3B
COSTS							
Capital Cost	US$ m	9 54	4 50	4 50	2 25	3 60	1 50
OM&R Cost	US$ m/year	0 48	0 11	0 27	0 06	0 27	0 25
EFFLUENT ALLOCATION							
On-site use	%	5	35	5	30	5	30
Industry	%	15	15	30	30	22	22
Agriculture	%	70	40	30	30	50	10
ECONOMIC VALUES							
Treatment	$/m3	0 25	0 25	0 20	0 20	0 15	0 15
On-site use	$/m3	0 88	0 95	0 33	0 33	0 11	0 19
Industry	$/m3	1 50	1 50	0 50	0 50	0 25	0 25
Agriculture	$/m3	0 75	0 75	0 15	0 15	0 05	0 05
RESULTS OF ANALYSIS							
Economic internal rate of return	%	26 6	36 0	17 4	36 6	9 7	43 2
Other Economic Indicators (calculated at 10% discount rate)							
Unit gross treatment cost	$/m3	0 49	0 49	0 30	0 19	0 23	0 12
Unit Net Treatment benefits	$/m3	0 51	0 51	0 09	0 21	0 00	0 20
Unit Cost of BOD Reduction	$/kg	1 04	1 04	1 78	1 13	1 37	0 69
Unit Cost of COD Reduction	$/kg	0 52	0 52	0 69	0 44	0 53	0 27

INDICATIVE ECONOMIC ANALYSIS - 1A

PLANT Activated Sludge
LOCATION Arid Sub tropical e g Jordan

YEAR	QUANTITY TREATED (MCM/YR)	COSTS (US$ Millions) Capital Outlay	OM&R*	Value of water used on site	Energy produced on site	Sludge disposal	Total costs	BENEFITS (US$ millions) Treatment benefit **	Value of on site use***	Value added in re use Industry	Irrigation	Total benefits	NET ECONOMIC CASHFLOW
1		0 95					0 95						0 95
2		3 34					3 34						3 34
3		3 82					3 82						3 82
4	1 43	1 43	0 16	0 06	0 00	0 02	1 67	0 36	0 00	0 32	0 75	1 43	0 24
5	2 91		0 32	0 13	0 00	0 04	0 48	0 73	0 00	0 66	1 53	2 91	2 43
6	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
7	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
8	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
9	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
10	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
11	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
12	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
13	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
14	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
15	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
16	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
17	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
18	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
19	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
20	4 34		0 48	0 19	0 00	0 05	0 72	1 09	0 00	0 98	2 28	4 34	3 62
												ECONOMIC INTERNAL RATE OF RETURN	26 6%

Cost and capacity estimates from
Stanley Consultants & Shubeilat Badran Assoc Upgrading & Expansion of Ba qa and Abu Nuseir Wastewater Treatment Plants Amman Jordan April 1995

CRITICAL PARAMETERS & ASSUMPTIONS

Design Peak Capacity (MLD)		14 9
Design Operating Capacity (MLD)		11 9
Design Influent Quality	BOD mg/l	500
	COD mg/l	1000
Design Effluent Quality	BOD mg/l	30
	COD mg/l	60
Qty treated at design operating cap (MCM/yr)		4 34
Fraction used on site		5%
Fraction allocated to industry		15%
Fraction allocated to irrigation		70%
Fraction not re used		10%
Capital Cost (US$m)		9 54
OM&R (Fraction of Capital Cost)		5%
On site energy prod (Fraction of O&M)		0%
Unit Sludge Production (MT/MCM/yr)		50
Unit cost of sludge disposal (US$/MT)		25
Treatment benefit ($/m3)		0 25
Unit value added in on site production ($/m3)		0 00
Unit value of water consumed on site ($/m3)****		0 88
Unit value added in re use ($/m3)		
Industry		1 50
Irrigation		0 75

COST INDICATORS

	Discount Rate 8%	10%	12%
Unit gross treatment cost ($/m3)	0 35	0 37	0 38
Unit net treatment benefits ($/m3	0 44	0 39	0 41
Unit cost of BOD reduction ($/kg)	0 75	0 78	0 81
Unit cost of COD reduction ($/kg)	0 34	0 39	0 41

NOTES

* Operation Maintenance & Equipment Replacement (intermittent replacements annualized)
** Treatment Benefit represents an estimate of the value of environmental costs avoided
*** On site production may include fish farming or biomass production for poultry feed (e g duckweed)
**** Unit value of water used on site represents the opportunity cost of not re using it for other purposes downstream (this is accordingly a calculated result not an input number)

INDICATIVE ECONOMIC ANALYSIS - SCENARIO 1B

PLANT UASB followed by Duckweed & Fish ponds
LOCATION Arid Sub tropical e g Jordan

YEAR	QUANTITY TREATED (MCM/YR)	COSTS (US$ Millions) Capital Outlay	OM&R*	Value of water used on site	Energy produced on site	Sludge disposal	Total costs	BENEFITS (US$ millions) Treatment benefit	Value of on site use**	Value added in re use Industry	Irrigation	Total benefits	NET ECONOMIC CASHFLOW
1		0 45					0 45						0 45
2		1 58					1 58						1 58
3		1 80					1 80						1 80
4	1 43	0 68	0 04	1 45	0 02	0 00	2 15	0 36	0 38	0 32	0 43	1 49	0 66
5	2 91		0 08	1 45	0 04	0 01	1 50	0 73	0 76	0 66	0 87	3 02	1 52
6	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
7	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
8	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
9	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
10	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
11	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
12	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
13	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
14	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
15	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
16	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
17	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
18	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
19	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
20	4 34		0 11	1 45	0 06	0 01	1 52	1 09	1 14	0 98	1 30	4 51	2 99
										ECONOMIC INTERNAL RATE OF RETURN			36 0%

CRITICAL PARAMETERS & ASSUMPTIONS

Design Peak Capacity (MLD)		14 9
Design Operating Capacity (MLD)		11 9
Design Influent Quality	BOD mg/l	500
	COD mg/l	1000
Design Effluent Quality	BOD mg/l	30
	COD mg/l	60
Qty treated at design operating cap (MCM/yr)		4 34
Fraction used on site		35%
Fraction allocated to industry		15%
Fraction allocated to irrigation		40%
Fraction not re used		10%
Capital Cost (US$m)		4 50
OM&R (Fraction of Capital Cost)		2 5%
On site energy prod (Fraction of O&M)		50%
Unit Sludge Production (MT/MCM/yr)		10
Unit cost of sludge disposal (US$/MT)		25
Treatment benefit ($/m3)		0 25
Unit value added in on site production ($/m3)		0 75
Unit value of water consumed on site ($/m3)****		0 95
Unit value added in re use ($/m3)		
Industry		1 50
Irrigation		0 75

COST INDICATORS

	Discount Rate 8%	10%	12%
Unit gross treatment cost ($/m3)	0 35	0 37	0 38
Unit net treatment benefits ($/m3	0 44	0 39	0 41
Unit cost of BOD reduction ($/kg)	0 75	0 78	0 81
Unit cost of COD reduction ($/kg)	0 34	0 39	0 41

NOTES

* Operation Maintenance & Equipment Replacement (intermittent replacements annualized)

** Treatment Benefit represents an estimate of the value of environmental costs avoided

*** On site production may include fish farming or biomass production for poultry feed (e g duckweed)

**** Unit value of water used on site represents the opportunity cost of not re using it for other purposes downstream (this is accordingly a calculated result not an input number)

INDICATIVE ECONOMIC ANALYSIS - SCENARIO 2A

PLANT Activated Sludge
LOCATION Humid Sub tropical e g Colombia

YEAR	QUANTITY TREATED (MCM/YR)	COSTS (US$ Millions) Capital Outlay	OM&R*	Value of water used on site	Energy produced on site	Sludge disposal	Total costs	BENEFITS (US$ millions) Treatment benefit **	Value of on site use **	Value added in re use Industry	Irrigation	Total benefits	NET ECONOMIC CASHFLOW
1		0 45					0 45						0 45
2		1 58					1 58						1 58
3		1 80					1 80						1 80
4	1 45	0 68	0 09	0 02	0 00	0 11	0 90	0 29	0 00	0 22	0 07	0 57	0 33
5	2 93		0 18	0 05	0 00	0 22	0 45	0 59	0 00	0 44	0 13	1 16	0 71
6	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
7	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
8	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
9	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
10	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
11	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
12	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
13	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
14	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
15	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
16	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
17	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
18	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
19	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
20	4 38		0 27	0 07	0 00	0 33	0 67	0 88	0 00	0 66	0 20	1 73	1 06
												ECONOMIC INTERNAL RATE OF RETURN	17 4%

CRITICAL PARAMETERS & ASSUMPTIONS

Design Peak Capacity (MLD)		15 0
Design Operating Capacity (MLD)		12
Design Influent Quality	BOD mg/l	200
	COD mg/l	500
Design Effluent Quality	BOD mg/l	30
	COD mg/l	60
Qty treated at design operating cap (MCM/yr)		4 38
Fraction used on site		5%
Fraction allocated to industry		30%
Fraction allocated to irrigation		30%
Fraction not re used		35%
Capital Cost (US$m)		4 50
OM&R (Fraction of Capital Cost)		6%
On site energy prod (Fraction of O&M)		0%
Unit Sludge Production (T/MCM/yr)		300
Unit cost of sludge disposal (US$/T)		25
Treatment benefit ($/m3)		0 2
Unit value added in on site production ($/m3)		0 00
Unit value of water consumed on site ($/m3)****		0 33
Unit value added in re use ($/m3)		
Industry		0 50
Irrigation		0 15

COST INDICATORS

	Discount Rate 8%	10%	12%
Unit gross treatment cost ($/m3)	0 22	0 23	0 23
Unit net treatment benefits ($/m3	0 09	0 07	0 07
Unit cost of BOD reduction ($/kg)	1 32	1 34	1 36
Unit cost of COD reduction ($/kg)	0 45	0 52	0 53

NOTES

* Operation Maintenance & Equipment Replacement (intermittent replacements annualized)

* Treatment Benefit represents an estimate of the value of environmental costs avoided

* * On site production may include fish farming or biomass production for poultry feed (e g duckweed)

**** Unit value of water used on site represents the opportunity cost of not re using it for other purposes downstream (this is accordingly a calculated result not an input number)

INDICATIVE ECONOMIC ANALYSIS - SCENARIO 2B

PLANT UASB followed by Duckweed & Fish ponds
LOCATION Humid Sub tropical e g Colombia

YEAR	QUANTITY TREATED (MCM/YR)	COSTS (US$ Millions) Capital Outlay	OM&R*	Value of water used on site	Energy produced on site	Sludge disposal	Total costs	BENEFITS (US$ millions) Treatment benefit **	Value of on site use***	Value added in re use Industry	Irrigation	Total benefits	NET ECONOMIC CASHFLOW
1		0 23					0 23						0 23
2		0 79					0 79						0 79
3		0 90					0 90						0 90
4	1 45	0 34	0 02	0 14	0 01	0 02	0 51	0 29	0 20	0 22	0 07	0 77	0 26
5	2 93		0 04	0 29	0 02	0 04	0 34	0 59	0 40	0 44	0 13	1 16	0 82
6	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
7	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
8	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
9	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
10	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
11	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
12	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
13	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
14	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
15	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
16	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
17	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
18	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
19	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
20	4 38		0 06	0 43	0 03	0 05	0 51	0 88	0 59	0 66	0 20	1 73	1 22
												ECONOMIC INTERNAL RATE OF RETURN	36 6%

CRITICAL PARAMETERS & ASSUMPTIONS

Design Peak Capacity (MLD)		15 0
Design Operating Capacity (MLD)		12
Design Influent Quality	BOD mg/l	200
	COD mg/l	500
Design Effluent Quality	BOD mg/l	30
	COD mg/l	60
Qty treated at design operating cap (MCM/yr)		4 38
Fraction used on site		30%
Fraction allocated to industry		30%
Fraction allocated to irrigation		30%
Fraction not re used		10%
Capital Cost (US$m)		2 25
OM&R (Fraction of Capital Cost)		2 5%
On site energy prod (Fraction of O&M)		50%
Unit Sludge Production (MT/MCM/yr)		50
Unit cost of sludge disposal (US$/MT)		25
Treatment benefit ($/m3)		0 20
Unit value added in on site production ($/m3)		0 45
Unit value of water consumed on site ($/m3)****		0 33
Unit value added in re use ($/m3)		
Industry		0 50
Irrigation		0 15

COST INDICATORS

	Discount Rate 8%	10%	12%
Unit gross treatment cost ($/m3)	0 14	0 14	0 14
Unit net treatment benefits ($/m3	0 17	0 16	0 14
Unit cost of BOD reduction ($/kg)	0 85	0 85	0 85
Unit cost of COD reduction ($/kg)	0 28	0 33	0 33

NOTES

* Operation Maintenance & Equipment Replacement (intermittent replacements annualized)
** Treatment Benefit represents an estimate of the value of environmental costs avoided
** On site production may include fish farming or biomass production for poultry feed (e g duckweed)
**** Unit value of water used on site represents the opportunity cost of not re using it for other purposes downstream (this is accordingly a calculated result not an input number)

INDICATIVE ECONOMIC ANALYSIS - SCENARIO 3A

PLANT Activated Sludge
LOCATION Extra Humid Sub tropical e g Bangladesh

YEAR	QUANTITY TREATED (MCM/YR)	COSTS (US$ Millions) Capital Outlay	OM&R*	Value of water used on site	Energy produced on site	Sludge disposal	Total costs	BENEFITS (US$ millions) Treatment benefit **	Value of on site use***	Value added in re use Industry	Irrigation	Total benefits	NET ECONOMIC CASHFLOW
1		0 36					0 36						0 36
2		1 26					1 26						1 26
3		1 44					1 44						1 44
4	1 45	0 54	0 09	0 01	0 00	0 07	0 70	0 22	0 00	0 08	0 04	0 33	0 37
5	2 93		0 18	0 02	0 00	0 13	0 33	0 44	0 00	0 16	0 07	0 67	0 35
6	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
7	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
8	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
9	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
10	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
11	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
12	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
13	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
14	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
15	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
16	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
17	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
18	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
19	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
20	4 38		0 27	0 02	0 00	0 20	0 49	0 66	0 00	0 24	0 11	1 01	0 52
												ECONOMIC INTERNAL RATE OF RETURN	9 7%

CRITICAL PARAMETERS & ASSUMPTIONS

Design Peak Capacity (MLD)		15 0
Design Operating Capacity (MLD)		12
Design Influent Quality	BOD mg/l	200
	COD mg/l	500
Design Effluent Quality	BOD mg/l	30
	COD mg/l	60
Qty treated at design operating cap (MCM/yr)		4 38
Fraction used on site		5%
Fraction allocated to industry		22%
Fraction allocated to irrigation		50%
Fraction not re used		23%
Capital Cost (US$m)		3 60
OM&R (Fraction of Capital Cost)		7 5%
On site energy prod (Fraction of O&M)		0%
Unit Sludge Production (T/MCM/yr)		300
Unit cost of sludge disposal (US$/T)		15
Treatment benefit ($/m3)		0 15
Unit value added in on site production ($/m3)		0 00
Unit value of water consumed on site ($/m3)****		0 11
Unit value added in re use ($/m3)		
Industry		0 25
Irrigation		0 05

COST INDICATORS

	Discount Rate 8%	10%	12%
Unit gross treatment cost ($/m3)	0 17	0 17	0 18
Unit net treatment benefits ($/m3	0 01	0 00	0 00
Unit cost of BOD reduction ($/kg)	1 01	1 03	1 05
Unit cost of COD reduction ($/kg)	0 34	0 40	0 40

NOTES

* Operation Maintenance & Equipment Replacement (intermittent replacements annualized)
** Treatment Benefit represents an estimate of the value of environmental costs avoided
*** On site production may include fish farming or biomass production for poultry feed (e g duckweed)
**** Unit value of water used on site represents the opportunity cost of not re using it for other purposes downstream (this is accordingly a calculated result not an input number)

INDICATIVE ECONOMIC ANALYSIS - SCENARIO 3B

PLANT UASB followed by Duckweed & Fish ponds
LOCATION Humid Sub tropical e g Bangladesh

YEAR	QUANTITY TREATED (MCM/YR)	COSTS (US$ Millions) Capital Outlay	OM&R*	Value of water used on site	Energy produced on site	Sludge disposal	Total costs	BENEFITS (US$ millions) Treatment benefit *	Value of on site use***	Value added in re use Industry	Irrigation	Total benefits	NET ECONOMIC CASHFLOW
1		0 15					0 15						0 15
2		0 53					0 53						0 53
3		0 60					0 60						0 60
4	1 45	0 23	0 01	0 08	0 01	0 01	0 32	0 22	0 15	0 08	0 01	0 46	0 13
5	2 93		0 03	0 17	0 01	0 02	0 20	0 44	0 31	0 16	0 01	0 92	0 72
6	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
7	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
8	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
9	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
10	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
11	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
12	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
13	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
14	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
15	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
16	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
17	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
18	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
19	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
20	4 38		0 04	0 25	0 02	0 03	0 30	0 66	0 46	0 24	0 02	1 38	1 08
												ECONOMIC INTERNAL RATE OF RETURN	43 2%

CRITICAL PARAMETERS & ASSUMPTIONS

Design Peak Capacity (MLD)		15 0
Design Operating Capacity (MLD)		12
Design Influent Quality	BOD mg/l	200
	COD mg/l	500
Design Effluent Quality	BOD mg/l	30
	COD mg/l	60
Qty treated at design operating cap (MCM/yr)		4 38
Fraction used on site		30%
Fraction allocated to industry		22%
Fraction allocated to irrigation		10%
Fraction not re used		38%
Capital Cost (US$m)		1 50
OM&R (Fraction of Capital Cost)		2 5%
On site energy prod (Fraction of O&M)		50%
Unit Sludge Production (MT/MCM/yr)		50
Unit cost of sludge disposal (US$/MT)		15
Treatment benefit ($/m3)		0 15
Unit value added in on site production ($/m3)		0 35
Unit value of water consumed on site ($/m3)****		0 19
Unit value added in re use ($/m3)		
Industry		0 25
Irrigation		0 05

COST INDICATORS

	Discount Rate 8%	10%	12%
Unit gross treatment cost ($/m3)	0 09	0 09	0 09
Unit net treatment benefits ($/m3	0 16	0 15	0 13
Unit cost of BOD reduction ($/kg)	0 52	0 52	0 53
Unit cost of COD reduction ($/kg)	0 18	0 20	0 20

NOTES

* Operation Maintenance & Equipment Replacement (intermittent replacements annualized)
** Treatment Benefit represents an estimate of the value of environmental costs avoided
*** On site production may include fish farming or biomass production for poultry feed (e g duckweed)
**** Unit value of water used on site represents the opportunity cost of not re using it for other purposes downstream (this is accordingly a calculated result not an input number)

Madras: Treated Sewage for Agriculture, Groundwater Recharge

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Conference on
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The Rural-Urban Connection

September 23 24 1996
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Washington D C

INDIA MADRAS - RENOVATED SEWAGE FOR AGRICULTURE, INDUSTRY AND GROUNDWATER RECHARGE

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L Panneer Selvam

SYNOPSIS

1 Madras city and its suburban areas have been experiencing perennial acute shortage of water for the past several years Increasing urban population decreasing groundwater table and insufficient rainfall have all contributed to the critical water supply situation Forced by necessity the Madras Metropolitan Water Supply and Sewerage Board (MMWSSB), which is responsible for delivering water supply services started experiments on the use of the renovated sewage for industry agro-forestry and groundwater recharge

2 The successful experience gained in using renovated sewage by large-scale industries has led to launching one of the largest sewage reclamation projects in the world The 130 mld capacity plant to supply renovated sewage to fourteen industries is expected to be completed by the year 2000 Encouraged by the success of the experiment to use renovated sewage in agro-forestry projects MMWSSB was instrumental in enacting a Groundwater Regulation Act in 1987 to control the unrestricted exploitation of groundwater and arrest the salinity intrusion

3 This paper reviews MMWSSB's experiences and outlines its future plans to promote large-scale use of renovated sewage for groundwater recharge, agro-forestry and industrial consumption

MADRAS CITY PROFILE

4 Madras, one of the five major metropolitan cities of India, is located on the south-eastern coast of the Indian peninsula The city has a tropical climate, and temperatures range from 41 to 18 degree Celsius The city gets an average annual rainfall of about 1000 mm, distributed between June/July (south-west monsoon) and October to December (north-east monsoon) months Per 1991 census, 4 2 million people live in an area of 170 sq km [3]

FRESH WATER DEMAND VERSUS SUPPLY

5 Madras city and its suburbs depend on rainfed reservoirs and groundwater aquifers to meet drinking industrial and irrigation water requirements As shown in Figure 1 there is a shortfall of 500 million liters per day (mld), equal to 50 percent between demand and supply

6 The current demand for domestic water supply to serve 4 5 million people at a modest service level of 140 liters per capita per day (lpcd) is estimated to be 630 mld However, only about 280 mld of water, equivalent to 45 percent of demand is supplied daily at the consumer end for one to three hours As a result, people of Madras are partly dependent on two additional sources (i) domestic groundwater from open dug

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[3]The current (1996) population of about 4 5 million is estimated to reach 5 13 million in the year 2001

well or bore well, and (ii) commercial groundwater supply services by private water vendors It is estimated that these two sources meet only about 12 percent of total demand, of which ten percent is from domestic groundwater sources Exploiting the water scarcity situation, the private water vendors charge the consumers from Rs 25 to 45 per kilolitre, as compared to a flat rate of Rs 30 per month per connection charged by MMWSSB

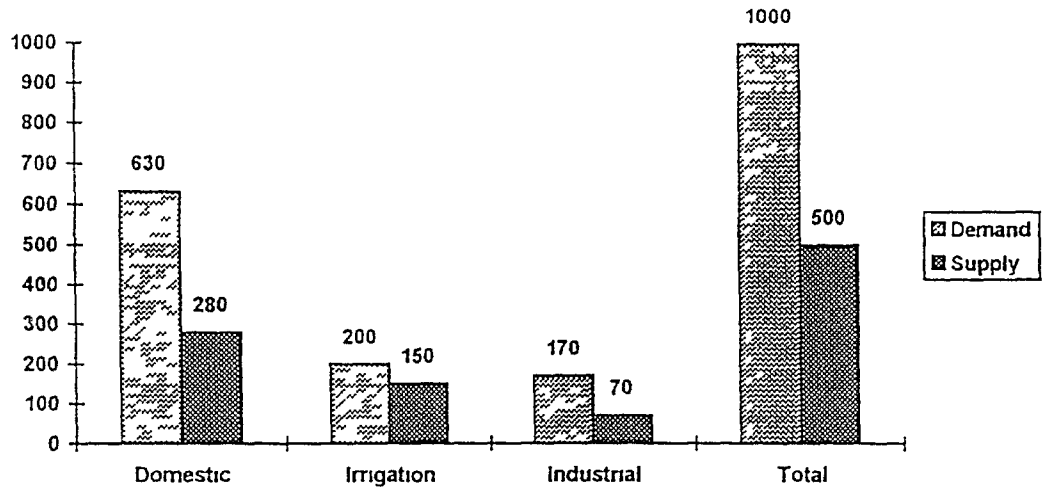

Figure 1 Fresh Water Demand Vs Supply in MLD (1996)

7 Due to growing population and improvement in the current services level, the domestic water demand in the year 2011 is estimated to reach about 1570 mld an increase of about 250 percent However during the same period the demand for industrial purpose is expected to grow only marginally and the irrigation demand is likely to fall due to increased urbanization of suburban areas

8 The current supply level of 500 mld is met from three major sources - (i) 270 mld from rainfed reservoirs (ii) 200 mld from groundwater aquifers and (iii) 30 mld from renovated sewage

EXCESSIVE GROUNDWATER EXTRACTION AND SALINITY INTRUSION

9 Indiscriminate and continuous extraction of groundwater by private water supply vendors contributed to salinity intrusion into the coastal aquifer This was particularly prominent in the northern part of the city where the saltwater incursion, limited to 3 km from the coastline in 1969, has progressed inwards to 7 km in 1983 and 9 km in 1987 As a result the private water supply vendors began moving towards the southern coastal aquifer Large-scale groundwater mining and the likely salinity intrusion in the southern parts of Madras as well created a virtual panic and called for immediate corrective measures

10 The MMWSSB's response to meet the increasing gap between demand and supply was two pronged (i) groundwater management and (ii) use of renovated sewage for industrial and agro-forestry uses The major project to augment the supply is to bring 960 mld of the Krishna River s water from the neighboring state of Andhra Pradesh This project initiated in 1983 includes construction of a 420 km long open canal and is expected to be completed by the year 2000

Groundwater Management

11 In order to regulate indiscriminate extraction of groundwater and to arrest salinity intrusion MMWSSB started implementing the following corrective measures

a MMWSSB was instrumental in the enacting, for the first time in India a groundwater act called the Madras Metropolitan Area Groundwater (Regulation) Act The purpose of this Act was to regulate and control the extraction use or transport of groundwater and to conserve groundwater in certain areas of Tamil Nadu Under this Act, which is implemented by MMWSSB certain notified areas would require prior permission and license for commercial use of groundwater Offenders are liable to punishment with fine and/or imprisonment Strict enforcement of this Act, since 1988 has helped in improving the groundwater table of the southern coastal aquifer by two to three meters

b In order to augment groundwater supply for irrigation MMWSSB constructed two check dams in 1992 in the Kortlayar River course 25 km north-west of Madras These check dams helped in storing the flood water and improving the groundwater level, even when the monsoon failed For example in summer 1991 despite a good monsoon with 1573 mm rainfall the groundwater level was as low as 23 5 m After the construction of check dams, the groundwater table started improving steadily and by summer 1995 it was as high as 14 5 m even though recorded rainfall was only 809 mm

c Another project along the northern coast was begun on a pilot scale to contain salinity intrusion and to improve the quality of water Fifteen groundwater recharge bore wells of 350 mm diameter were drilled into the aquifer and fresh water from distant sources was used for recharge a scheme commissioned in 1992

d Starting from the year 1993 MMWSSB is also promoting rainwater harvesting measures Now it is mandatory under the building bylaws to install facilities to harvest rainwater for groundwater recharge New water service and sewerage connections are given only on the basis of compliance of the rainwater harvesting measures A major project for collecting rainwater and conserving the same through pumped storage schemes has also been taken up for implementation in 1996

Use of Renovated Sewage For Industry

12 Industrial water demand approximately 15 percent of the total demand receives a lower priority, especially during the drought periods While domestic water supply has to be maintained to the maximum extent possible industrial supply is progressively reduced depending on the gravity of the situation For example during the worst water scare year of 1987 the industrial water supply was fully shut down for a period of six months and the domestic water supply was curtailed substantially with alternate day supplies for over ten months

13 In the early eighties, MMWSSB evaluated the options for recycling sewage for industrial use Pilot treatment plants were set up in two of its sewage treatment plans at Koyambedu and Kodungaiyur to develop design parameters and evaluate their feasibility Despite the encouraging results none of the industries came forward to install their own sewage renovation plants This was mainly due to requirements of large investments and lack of confidence to use renovated sewage

14 Unprecedented drought in 1987 motivated two large-scale process industries to respond to MMWSSB's suggestion [4] In 1992, the Madras Refineries Limited (MRL) and the Madras Fertilizers Limited (MFL) installed their captive sewage renovation plants to treat 17 and 13 mld respectively of sewage These two plants are operating satisfactorily and the average sewage characteristics at each stage of treatment as reported by these companies, are given in Table 1 Prior to 1992 these industries were fully dependent on groundwater to meet their demand of 45 mld In 1996, 55 percent of their demand is met from renovated sewage and the rest from groundwater sources

Table 1 Average sewage characteristics after each stage of treatment

Treatment Process Steps	BOD mg/l	SS mg/l	TDS mg/l	Amm N mg/l	Nitrate mg/l	Phosphate mg/l
Raw sewage	400	480	1500	85	Nil	40
Pre-treated Sewage - Screening and grit removal	390	460	1500	85	Nil	40
Primary Treatment - Primary settling	280	200	1500	85	Nil	40
Secondary Treatment - Activated sludge process	20	30	1500	Nil	20	15
Tertiary Treatment - Chemical treatment/settling	5	5	1500	Nil	20	Nil
Final Treatment (polishing) - Micro filtration & Reverse osmosis	Nil	Nil	500	Nil	5	Nil

15 Economics The capital investment excluding the cost of land, incurred by these industries was about 0 34 million $US per mld of installed capacity MFL and MRL spent Rs 200 million (5 7 million $US) and Rs 150 million (4 3 million $US) respectively MMWSSB leased out about 40 ha of land at the Kodungaiyur treatment plant site for the next 30 years Also the secondary treated sewage is supplied to MFL and MRL at a cost of Rs 4 per kilolitre Although the financial cost of renovated sewage—about Rs 40 per kilolitre—was about 60 percent higher than the cost charged by MMWSSB—Rs 25 per kilolitre—the additional economic benefits were in favor of sewage renovation Key economic benefits included uninterrupted availability of renovated sewage For example, in 1993 when all other industries were forced to shut down, MFL and MRL continued with their production by meeting 75 percent of their water requirements Also TDS level in the renovated sewage was about 500 mg/l, less than that of groundwater s 800 to 1000 mg/l, and industries could decrease their cooling water requirements

16 One more plant Encouraged by the success of MFL and MRL another large-scale petrochemical industry in the private sector, Southern Petrochemical Industries has now come forward to install a 17 mld sewage renovation plant and has sought the assistance of MMWSSB in design and construction of the proposed plant It has already deposited Rs 50 million as advance payment towards capital cost with the MMWSSB and the design work is in progress This plant is expected to be commissioned by 1998 and will come up at the existing Kodungaiyur sewage treatment plant site

Other key reasons to go in for sewage renovation were (i) MFL and MRL being large scale public sector undertakings could afford the investments (ii) their inherent process designs did not permit any interruption in their production and water was a critical input and (iii) strict enforcement of the Groundwater Act and non availability of other sources of water

17 Key lessons learnt from the MRL and MFL experience were (i) partnership between utilities such as MMWSSB and the private sector is essential to promote large-scale use of renovated sewage and (ii) while large-scale industries could afford their own sewage renovation plants large numbers of small scale industries do not have adequate financial and technical capacities to install operate and maintain their own sewage renovation plants Also, laying and maintaining individual distribution networks for secondary treated sewage will be an expensive proposition

18 Madras Sewerage Renovation and Functional Improvement Project (1996-2000) The MMWSSB is currently implementing a large-scale renovation project with the financial assistance from the Japanese Overseas Economic Cooperation Fund (OECF) This project costing Rs 5 720 million (163 5 million $US) will produce 100 mld of renovated sewage in the year 2000 Fourteen small and medium scale industries located in a north Madras industrial estate, have agreed to buy the entire quantity at Rs 30 per kilolitre,[1] including a 10 percent annual escalation in price At present these industries pay Rs 25 per kilolitre of water supplied by MMWSSB The project has been evaluated to be economically viable and capable of repaying the loan (85 percent of total project costs) in 30 years

Use Of Sewage For Agro-Forestry

19 In the past several years, MMWSSB has been growing paragrass (Bracharia Mutica) in its 780 ha of secondary treated sewage-fed farmland Irrigation by flooding combined with regular larvaecide spraying to control mosquito breeding and occasional use of insecticides, particularly during winter months gave a yield of 60 to 80 tons of paragrass or Rs 12,000 to 16 000 per ha per year The right to irrigate and harvest each parcel of farmland was auctioned every year which was just sufficient to meet the expense incurred by MMWSSB in maintaining the farmland

20 The sewage-fed cultivation of paragrass as cattle fodder once considered an economic use of sewage, was discovered to be a major environmental health hazard For example stagnation of sewage over large areas led to breeding of mosquitoes and small insects, odor problems and contamination of groundwater Also the large-scale availability of fodder encouraged cattle owners to retain their cattle even as municipal authorities were trying to relocate them outside city limits In 1990-91 with the growth of urban population around the sewage-fed farms, MMWSSB started experimental agro-forestry projects in about 8 ha of land at its Koyambedu and Nesapakkam sewage treatment plants The goals of this experiment carried out under expert supervision were to identify suitable species optimal irrigation and planting (spacing between two plants) methods that would use more sewage in less area and provide higher economic and environmental benefits After extensive monitoring for over two years, the following conclusions were reached

a) Basin irrigation methods with 3 m spacing were found to be better suited for Madras conditions,

b) Of the ten species tried, six species registered good growth They were (i) Leucaena (Subabul) (ii) Ailanthus Excelsa (Matchwood) (iii) Tectona Grandis (Teak), (iv) Cassia Siamea (Mayilkonnai), (v) Eucalyptus, and (vi) Bamboo

c) The timber value of these trees exceeded the receipts/benefits from cattle fodder and

d) The above species adapted themselves quickly to treated sewage exhibited good characteristics for bio-draining excess water and registered good growth rates (as shown below) both in the root and shoot system

[1] The cost of treated sewage is expected to be lower than Rs 40 per kl the current cost of treatment reported by MRL and MFL mainly because (i) economy of scale (ii) 10 years of moratorium on loan repayment and (iii) capital repayment spread over a period of twenty years

Species	Height	Girth (GBH)
(i) Leucaena (Subabul)	8 m	60 cm
(ii) Ailanthus Excelsa (Matchwood)	10 m	70 cm
(iii) Tectona Grandis (Teak)	10 m	40 cm
(iv) Cassia Siamea (Mayilkonnai)	8 m	80 cm
(v) Eucalyptus	10 m	70 cm
(vi) Bamboo	8 m	100 shoots

21 Encouraged by the positive results MMWSSB is currently developing an additional 100 ha of agro-forestry The Forest Department, Government of Tamil Nadu, is assisting MMWSSB in implementing the project at a total cost of Rs 5 million (0 14 million $US) It is estimated that about 30 mld of secondary treated sewage will be used to grow nine different species Timber value of these trees after five years will be about Rs 15 million, twice that of income from growing paragrass as cattle fodder

22 Another large-scale agro-forestry project to use 70 mld of secondary treated sewage in about 300-4000 ha of land is currently under preparation Implementation of this project is expected to commence in December 1996 In total, by the end of 1997 MMWSSB will be using about 100 mld of secondary treated sewage in 400 to 500 ha of agro-forestry

FUTURE PLANS FOR LARGE-SCALE USE OF RENOVATED SEWAGE

23 MMWSSB is pursuing various project options for large-scale recycling of renovated sewage for groundwater recharge, industrial use landscaping, etc The aim is to treat the city sewage as a resource for meeting conflicting water demands Key options under serious consideration are briefly described below

24 Groundwater Recharge - Coastal Injection MMWSSB has commissioned Tahal Consulting Engineers Ltd from Israel to evaluate the scope for integrated use of 100 mld of sewage currently treated at Perungudi, south of Madras The consultants are closely evaluating the option for coastal injection of 60 mld of renovated sewage to form a barrier against salinity incursion Such projects have been successfully executed in Orange County, California

25 Industrial Reuse New demand for about 200 mld of fresh water has been received from the proposed industrial complexes in North Madras To respond to this emerging demand, MMWSSB is currently preparing a Second Madras Sewage Renovation Project for further supply of about 200 mld of renovated sewage to new industries

26 Agriculture The rural hinterland of Madras city, particularly along the southern coast, has a tradition of farmers raising eucalyptus and casuarina trees on their agricultural lands Presently such cultivation is done under rainfed conditions Preliminary inquiries with Agriculture and Forest Department officials and farmers indicate excellent response to the potential for using treated sewage for raising casuarina and eucalyptus Under normal rainfed conditions these trees require a minimum of six years growth before they can be harvested mostly for the pulp industry Experts estimate that use of treated sewage for irrigation would reduce the harvest period by half It would be possible to make available through open channels up to 100 mld of treated sewage at a cost of Rs 4 per kilolitre to irrigate an area of approximately 250 to 500 hectares This option needs to be further evaluated for potential public health and environmental impacts of large-scale use of secondary treated sewage by farmers

27 Landscaping Large peri-urban areas particularly a stretch along the southern coast up to the Temple town of Mahabalipuram, approximately 40 km away from Madras city is presently developing as an extended recreational and tourist belt It is estimated that these upcoming tourist spots would require large quantities of water, about 133 mld for landscaping and other purposes This stretch which is also close to the Perungudi sewage treatment plant, can be supplied with treated sewage for landscaping This option needs to be evaluated in detail and discussions with potential users are taking place at present

CONCLUSION

28 Water is critically scarce in many parts of India Water utilities, with their fragmented management of the scarce water resources and neglect of intersectoral interactions within an interdependent system have failed to deliver sustainable services It is in this context MMWSSB s attempts to link drinking water supply, the environment, and economic development are relevant The key lessons for delivering sustainable water services that have emerged from these experiences are

a) We need to change the way we think about and manage water

b) It is financially and technically viable to use renovated sewage for industrial agricultural and groundwater recharge purpose

c) The high opportunity costs of reduced or non-supply of water make industries realize the economic benefits of investing in treatment and recycling of sewage

d) The facilitating role of utilities and local government (providing technical guidance, long-term leasing of land, installing centralized treatment and distribution networks, etc) is very useful,

e) Renovated sewage for agriculture particularly agro-forestry could become a financially and commercially viable proposition in water scarce areas, and

f) Supporting policy interventions such as the Groundwater Act and economic water pricing encourage the use of renovated sewage

29 The spin-off benefit is the likelihood of improved sanitation in small and medium sized towns For example, most of these towns in India do not have piped sewerage systems And due to lack of financial resources, the situation is unlikely to change in the near future The success in selling renovated sewage to industries in Madras and the financial returns have prompted both the MMWSSB and the municipality of a nearby suburban area—Tambaram—to seriously consider implementing a sewage system