Sustainable Treatment and Reuse of Municipal Wastewater

For Decision Makers and Practicing Engineers

Menahem Libhaber and Alvaro Orozco-Jaramillio

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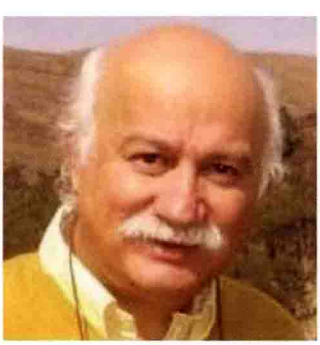
About the Authors

Menahem Libhaber, PhD, Consulting Engineer. Dr. Libhaber received an MSc in Chemical Engineering and a PhD in Water Resources and Environmental Engineering from the Technion, Israel Institute of Technology, Haifa, Israel. Prior to joining the World Bank in 1991, he worked for 18 years for the consulting firm Tahal Consulting Engineers as a water and sanitation engineer in Israel and many other countries including Brazil, Costa Rica, Peru, El Salvador, Chile, Mexico, Honduras, Turkey, Spain, Yugoslavia, and Nigeria. He served for three years as a consultant to UNEP - United Nations Environmental Program, the Mediterranean Action Plan. He joined the World Bank in 1991 as a Lead Water and Sanitation Engineer in the Latin America Region. He has served as task manager of water and sewerage projects in Colombia, Bolivia, Argentina, Costa Rica, the Dominican Republic, Peru, and Trinidad and Tobago. He has also worked on other projects in Brazil, Paraguay, St. Lucia, Guyana, Venezuela, Jamaica, Honduras, Panama, Haiti, India, and China. Many of these projects involved design and construction of wastewater treatment plants. Dr. Libhaber is Coauthor of the Book "Marine Wastewater Outfalls and Treatment Systems" (2010). He also published numerous articles and reports and delivered numerous presentations in international conferences and seminars. Dr. Libhaber retired from the World Bank in July 2009. He is presently a private consulting engineer to the World Bank and other institutions. E-mail: mlibhaber@gmail.com



Alvaro Orozco-Jaramillo, MSc, Consulting Engineer. Civil Engineer of the School of Mining, National University of Colombia (1971) and MSc in Sanitary Engineering of the Pennsylvania State University (1976). Worked in the fields of environmental engineering, water treatment, solid wastes management and global warming. Winner of the Award Diódoro Sánchez of the Colombian Society of Engineers in 1986 and Mention of Honor of the same award in 1981. Was also granted the Merit Award "World Water Year" in 2003 from the Commission of

Sanitary Engineering of the Colombian Society of Engineers, Category Academic-Investigator. Works as an International Consultant for the World Bank, the Inter-American Development Bank, Biwater and other institutions in various countries, including Brazil, Argentina, Uruguay, Bolivia, Central America, the Caribbean, Peru and Colombia. Was a professor in the Los Andes University in Bogota, Colombia, for 20 years and in the University of Antioquia, Colombia, in various opportunities. Author of the Textooks "Bioingeniería de Aguas Residuales" (2005) (Wastewater Bioengineering), "Desechos Sólidos" (1980) (Solid Wastes) and Coauthor of the book "Tratamiento Biológico de las Aguas Residuales" (1985) (Biological Wastewater Treatment). Also published numerous articles and delivered international presentations in conferences and seminars. E-mail: alvaro.orozco.jaramillo@hotmail.com

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Dedication

This book is dedicated to:

- The memory of my beloved parents Shifra and Jacob Libhaber
- My son Barak Libhaber
- My sister Klara Glesinger, her husband David and her Children Ronen, Iris and Merav
- Paula Dias Pini
- And to the memory of my dear friend, mentor and teacher Dr. Emanuel Idelvitch, who was taken from us before his time

Menahem Libhaber

- To my loving wife, Beatriz Munera, for a life of companionship and patience
- My daughters Lina and Fernanda and her husband, Rainer Viertel
- Last but not least, to my adored grandsons Friedrich and Martin Viertel-Orozco

Alvaro Orozco-Jaramillo

Preface

The uncontrolled disposal to the environment of municipal, industrial and agricultural liquid, solid and gaseous wastes constitutes one of the most serious threats to the sustainability of the human race by contaminating water sources, land and air, and by its potential contribution to global warming. With increasing population and economic growth, treatment and safe disposal of wastewater is essential to preserve public health and reduce intolerable levels of environmental degradation. In addition, adequate wastewater management is also required for preventing contamination of water bodies for the purpose of preserving the sources of clean water.

Effective wastewater management is well established in developed countries, but is still limited in developing countries. In most developing countries many people are lacking access to water and sanitation services. Collection and conveyance of wastewater out of urban neighborhoods is not yet a service provided to all the population and adequate treatment is provided only to a small portion of the collected wastewater, in most cases covering less than 10% of the municipal wastewater generated. In slums and peri-urban areas it is not rare to see raw wastewater flowing in the streets. The inadequate water and sanitation service is the main cause of diseases in developing countries.

In 2011 the population of the planet was 7 billion. Population growth forecasts indicate a rapid global population growth which will reach 9 billion in 2030. The forecasts also indicate that: (i) most of the population growth will occur in developing countries while the population of developed countries will remain constant at about 1 billion; and (ii) a strong migration from rural to urban areas will take place. Considering the expected population growth and the order of priorities in the development of the water and sanitation sector in developing countries (water supply and sewerage first and only then wastewater treatment), as well as the financial difficulties in these countries, it cannot be assumed that the current low percentage of the coverage of wastewater treatment in these countries will increase in the future, unless a new strategy is adopted and innovative, affordable wastewater treatment options are used. Application of appropriate wastewater treatment technologies, which are effective, low cost (in investment and especially in operation and maintenance), simple to operate, proven technologies, should be a key component in any strategy aimed at increasing the coverage of wastewater treatment. Appropriate technology processes are also more environment-friendly since they consume less energy and have therefore a positive impact on mitigating climate change effects. Also, with modern design, appropriate technology processes cause less environmental nuisance than conventional processes, for example they produce lower amounts of excess sludge and their odor problems can be effectively controlled.

Unfortunately the need to adopt appropriate technology processes is in many cases not understood to decision makers in developing countries. There is a tendency to apply cutting edge technologies consisting of highly mechanized, complex treatment plants which are of high investment costs and of high operation and maintenance costs. Investment financing for complex treatment plants can sometimes be mobilized in developing countries in the form of grants and/or soft loans; however, it is almost impossible to obtain grants or subsidies for operation and maintenance of such plants. Usually, the authorities (municipalities or water and sanitation utilities) do not have the capacity to finance high operation and maintenance costs of complex treatment plants from their internal cash generation, and so this type of treatment plants tend to deteriorate rapidly due to insufficient budget for operation and maintenance, and many of them are abandoned a short time after being commissioned. This indicates that complex plants are not sustainable in developing countries and points to the need for the employment of plants based on alternative, simpler and low cost appropriate technology processes.

A variety of unit process of appropriate technology with a proven track record are known and in operation for many years, each yielding a different effluent quality. Some provide low quality effluents and some, effluents of good quality. When an effluent quality higher than what a single unit process of appropriate technology can produce is required, a treatment plant consisting of a series of appropriate technology unit processes can be used (2, 3 or more), in which the effluent of the first unit process is fed into the second process for polishing and the effluent of the second process is fed to the third and so on, if necessary. This approach can produce practically any final effluent quality required. *The idea of the ability to combine unit processes to create a treatment plant based on a series of appropriate technology processes which jointly can generate any required effluent quality is the main message of this book.* A plant based on a combination in series of appropriate technology unit processes is still easy to operate and is usually of lower costs than conventional processes in terms of investments and certainly in operation and maintenance. So in essence, this book present the concept of sustainable appropriate technology processes and the basic engineering design procedures to obtain high quality effluents by treatment plants based on simple, low cost and easy to operate processes.

The concepts of appropriate technology for wastewater treatment and issues of strategy and policy for increasing wastewater treatment coverage are presented in the first part of the book. In the second part each chapter is dedicated to a selected unit process of appropriate technology and provides the scientific basis, the equations and the parameters required to design the unit processes, with some design and process innovations developed by the authors. The book also presents some chapters on design procedures for selected combined processes which are in use in developing countries. Once the fundamentals of each unit and combined process have been established, the book proposes in each chapter an innovative Orderly Design Method (ODM), easy to be followed by practicing engineers, using the equations and formulas developed in the first section of each chapter. At the end of each chapter, a numeric example for the basic design of each selected appropriate technology process is solved for a city with a population of 20,000 using the ODM and an Excel program which is provided to the readers for download from an online web site (http://www.iwawaterwiki.org/xwiki/bin/view/Articles/Software+Developed+for+Sustainable+Treatment+and+Reuse+of+Municipal+Wastewater). The book also presents ideas of many additional combinations of unit processes of appropriate technology, classified according to their adequacy for functioning in different temperature zones and in accordance with the size of land area occupied by the wastewater treatment plant. Finally, the book contains a chapter on climate change and the potential impact of wastewater treatment on climate change.

The book title contains the concept of sustainability of wastewater treatment. It is intuitively clear that the use of appropriate technology wastewater treatment plants can significantly enhance their sustainability. They are simple to operate and their operation and maintenance costs are low so there are no financial and technical difficulties to keep them adequately operating over an extended period of many years and no reason to abandon them a short time after their commissioning. However the sustainability aspects of appropriate technology treatment plants have a much wider scope. First they contribute to improving the overall environmental sustainability since the use of appropriate technology enables the expansion of the coverage of wastewater treatment in developing countries. In addition, appropriate technology processes can contribute to enhancing the sustainability of utilities in several ways: (i) by enhancing the financial sustainability of the utilities due to reduced investment as well as operation and maintenance costs; (ii) by enhancing the technical and operational sustainability of the treatment plants through the employment of simple to operate and maintain processes based on simple, mostly locally manufactured equipment; and (iii) by enhancing the institutional sustainability of the utilities since due to the limited financial demand and technical efforts, they do not present meaningful problems to the utilities' managements, do not impose additional managerial efforts, reduce the institutional burden and challenges of the water and sanitation utilities and thereby contribute to enhancing institutional sustainability. In fact, the use of appropriate technologies in wastewater treatment helps to alleviate the main problems of the water and sanitation sector in developing countries, which are: financial weakness, low technical capacity and institutional weakness, thereby contributing to improving the sustainability of the sector as a whole.

The inclusion in the book title of the concept of reuse (which refers to reuse of effluents for irrigation) requires an explanation. Seemingly the book contains only one chapter on reuse, chapter 7, which presents the concept of stabilization reservoirs as an important component of any reuse system, and applies an innovative algorithmic design approach. The proposed reuse concept provides that the general scheme of a reuse system consists of preliminary treatment followed by a stabilization reservoir. The preliminary treatment system can be any installation able to reduce the organic matter content of the wastewater to a level which prevents development of anaerobic conditions in the reservoir. If the pretreatment system is based on any one of the appropriate technology processes presented in the other chapters of the book, then the entire reuse system is an appropriate technology system. So in fact the entire book applies to wastewater reuse for irrigation. However, the focus of reuse in the book is on the technical aspects and design of reuse systems and practical implementation of reuse projects, and it does not analyze other aspects of reuse, which can be found in the professional literature.

Part 1 of the book (theory and concepts) is directed to policy and decision makers, utilities managers and staff, as well as to practitioners and scholars interested in concepts but not in design. The objective of Part 1 is to explain that there are alternatives to mechanized technologies which can be as effective in terms of effluent quality and advantageous from other perspectives. Part 2 of the book is directed to water and sanitation engineers, consulting firms, staff of water and sanitation utilities, project managers, water and sanitation practitioners, technicians and other professionals dealing with water and environmental issues, academic scholars, professors, teachers and students, providing them with an innovative tool which employs for each process an algorithmic Orderly Design Method applied through an Excel program to perform the calculations once the input information has been introduced.

Although the focus of the book is the resolution of wastewater treatment and disposal problems in developing countries, the concepts presented are valid and applicable anywhere and plants based on combined unit processes of appropriate technology can be used also in developed countries and provide to them the benefits described in the book.

The authors hope that the book provides information that will be of value to all who are involved in any way with wastewater treatment and disposal, including those involved in the decision-making process, those involved in the design of treatment plants, and those concerned with their environmental impacts. We especially hope that the book will contribute to rational choices of wastewater treatment and disposal schemes and to sound wastewater management, especially in developing countries.

Contents: The first part of the book presents the concepts of appropriate technology and of combining unit processes to achieve higher quality effluents, as well as issues of strategy and policy for expanding the coverage of wastewater treatment. The second part deals with the fundamentals of wastewater treatment, process design and design examples including: Decomposition Processes of Organic Matter, Calculation of Municipal Wastewater Flow and BOD Load, Rotating Micro Screens, Treatment in Stabilization Lagoons, Anaerobic Treatment (Upflow Anaerobic Sludge Blanket Reactor-UASB, Anaerobic Filter, Piston Anaerobic Reactor), Stabilization Reservoirs, Horizontal Flow Constructed Wetland, Chemically Enhanced Primary Treatment (CEPT), Other complementary processes like Sand Filtration, Dissolved Air Flotation (DAF) and UV Disinfection, as well as Combinations of appropriate Technology Processes: (i) Rotating Micro Screens Followed by UASB followed by Anaerobic Filter, (ii) Rotating Micro Screens Followed by UASB followed by Facultative Lagoons, (iii) Rotating Micro Screens Followed by UASB followed by Sand Filtration, (iv) Rotating Micro Screens Followed by CEPT followed by Sand Filtration, and (v) Rotating Micro Screens Followed by UASB followed by Anaerobic Filter followed by DAF followed by Membrane Filtration, and Global Warming and the impact of Wastewater Treatment on Climate Change.

Menahem Libhaber
Alvaro Orozco-Jaramillo

Nomenclature

a	Net area, m^2/m^3
a	Pipeline orifice area
a_p	Passing area in the UASB separator
a_g	Gas exit area of the UASB separator
A_J	Surface area of process J (i.e des: grit channel, s: settling basing, M: maturation lagoon, etc.)
A_p	Main pipeline area
AAL	Aerated Aerobic Lagoons
ABR	Anaerobic Baffle Reactor
ACF	Altitude Correction Factor (masl)
AD	Anaerobic digestion
AF	Anaerobic Filter
AMet	Methanogenic Activity
AOR	Actual Oxygen Requirement
A/S	Air to solids ratio
A/V	Area to volume ratio
A_a	Afferent area of infiltration, ha
A_c	Crop area in SR, ha
As	Surface area
A_T	Transversal area
A_{UASB}	Surface area of the UASB, m^2
α	Earth Albedo, approximately 0,30
α	Transfer correction factor of O_2, tap water/WW
B	Fecal Coliforms, MPN/100mL
B	Wetland width
BOD	Biochemical Oxygen Demand
BOD_5	Biochemical Oxygen Demand at day five
BOD_u	Ultimate Biochemical Oxygen Demand

BODT	Total BOD_5
β	Transfer correction factor of O_2 for salinity
c	Concentration, mg/L
C_0	Concentration of O_2 at operating conditions
C_s	Saturation concentration of O_2 at Standard Conditions
C_{sT}	Saturation concentration of O_2 at temperature T
CAESB	The water and sanitation utility of the Federal District of Brasilia, Brazil
Cal	Calories
CBOD	Carbonaceous BOD
CEMS	Chemically Enhanced Rotating Microscreening
CDM	Clean Development Mechanism
CEL	Cost-Effective Level, $kgBOD_{5r}/USD_i$
CEL	Cost-effective Level, $USD\$/kgCOD_r$
CEPT	Chemically Enhanced Primary Treatment
CER	Carbon Emission Reduction
CMAS	Completely Mixed Activated Sludge
CMI	Mean Investment Cost
CMLP	Mean Long-term Cost
CMO	Mean Operating Cost
Coli Fecal	FC, NMP/100 mL
COD	Chemical Oxygen Demand
COPASA	The water and sanitation utility of the State of Minas Gerais, Brazil
CO_2	Carbon Dioxide
CRE	The Power Utility of Santa Cruz, Bolivia
CRT	Cell retention time, θ_c (Sludge Age)
CWW	Combined waste waters
d	Particle effective size
d	Dispersion factor
D	Dose UV, $W \cdot s/m^2$ or J/m^2.
D	Axial dispersion coefficient, m^2/h
DAF	Dissolved air flotation (or diffused)
DNA	Deoxyribonucleic Acid
DO	Dissolved Oxygen, mg/L
DOM	Degradable Organic Matter
DTC	Developing and Transition Countries
DWW	Domestic wastewater
DWWT	Domestic Wastewater Treatment
D_{10}	Sand effective size
D_T	Drum diameter of a MS, m
D_w	Total monthly demand for agriculture water in a SR, $m^3/ha \cdot mes$
ΔCH_4	Methane produced, mg/L CH_4
$\Delta G^{\circ\prime}$	Standard free energy, kJ/reaction
$\Delta G'$	Real free energy, kJ/reaction
Δh	Hydraulic head loss
ΔO_2	Oxygen uptake, mg/L of O_2

ΔS	Substrate Removal, mg/L BOD_u or COD
ΔX	Biomass Production, mg/L SSVLM
EF	Emission Factor
EHSA	Extremely High Sludge Ages
ET	Real evapotranspiration, mm/month
ET_0	Evapotranspiration Potential, mm/month
EU	European Union
EW	Equivalent Weight, eq/L
ε_0	Bed porosity
f	Factor of proportionality in photosynthetic lagoons, 0.5 m/d
FC	Fecal Coliforms
FLC	Food limiting conditions
F_{O2}	Oxygenation factor
FDS	Fixed Dissolved Solids
FSS	Fixed Suspended Solids
F/M	Organic Load, kg COD/kg MLVSS · d
φ	Granule form factor; 1 if spherical
G	Hydraulic Gradient, s^{-1}
GCM	Global Climate Model
GHG	Greenhouse Gases
GSLS	Gas-Solid-Liquid Separator, in a UASB and PAR
GSLS-SM	Standard Model of the Gas-Solid-Liquid Separator, in a UASB and PAR
γ	Water specific weight, N/m^3
σ	Boltzmann's Constant, $5{,}6697 \times 10^{-8}$ W/m^2K^4
h	Head loss, depth, m
h	Depth
h_f	Head loss, m
ha	Hectare
H	Depth
H_J	Depth of process J (i.e UASB, lagoon, etc.)
H_G	UASB's GSLS Depth
H_L	UASB's Sludge depth
H_T	UASB's Total depth
HCR	Hydrograph Controlled Release
HDT	Hydraulic detention time, t_d
HDPE	High Density Poly Ethylene
HP	Horse power
I	UV Ray intensity, W/m^2
IAT	Innovative Appropriate Technology
IO	Inverse Osmosis
IPCC	Intergovernmental Panel on Climate Change
IWW	Industrial wastewater
IWWT	Industrial Wastewater Treatment
k	Eckenfelder's equation constant
k	Anaerobic metabolic change rate

k	Bottle constant of the CBOD base e
K	Bottle constant of the CBOD base 10
K	Screens Coefficient
K_B	FC removal constant
K_H	Henry's constant
K_{Hi}	Wetland constant of first order for i = BOD_5, TKN, NO_3 and FC, d^{-1}
K_p	First order area constant for P. K_p is 0,0273 m/d, in SSFCW
K_h	Proportional constant of Percolator Filter
K_{La}	Aeration Coefficient
K_O	Orozco's constant (depends on θ_c)
K_w	Ion product constant, $[H+][OH-] = 1 \times 10^{-14}$
k_0	Net maximum rate of substrate removal
k_c	Contois saturation constant
k_c	Coefficient of each crop (ET real on ET_0)
k_e	Endogenous Coefficient, d^{-1}
k_L	McKinney's equation constant
k_m	Monod's saturation constant
k_s	Hydraulic Conductivity, m/d
KWH	Kilo Watt Hour
L	Remnant CBOD, mg/L
L	Length, m
L	Liter
l	Liter
LAC	Latin America and Caribbean Region
LAS	Low Power Level mixers
Lps	Liters per second
L_{BOD}	DBO load, kg/d
L_{OD}	Dissolved Oxygen Load, kg/d
L_q	Air load in the biofilter
L_s	Surface Organic Load, $kgBOD_5/ha \cdot d$
L_v	Volumetric Organic Load, kg $/m^3 \cdot d$ BOD_5 or sCOD
L/w	Length to width ratio
λ	Substrate maximum biodegradability, %
m	$-K_h/q_a n$ in percolating filter
MBR	Membrane Biological Reactor
MCF	Methane correction factor
MF	Micro Filtration
ML	Mixed Liquor
MLC	Mass limiting conditions
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
MPN	Most Probable Number, E-Coli per 100 mL
MPS	Method of Process Selection
MS	Micro Screens
MW	Molecular Weight, g/mole

masl	Meters above sea level
mole	Gram molecular weight
n	Potential constant of Percolating Filter
n	Manning's rugosity coefficient
n	Filter media Porosity, %
NF	Nanofiltration
n	Undefined number
η	Methane Concentration in biogas
NBOD	Nitrogenous Biochemical Oxygen Demand
NH_3	Ammonia
NO_3	Nitrate
N_0	O_2 Transfer of mixing aerator, kg/h · HP
O_2	Oxygen, mg/L
ODM	Orderly Design Method
OECD	High Income Countries (members of the Organization of Economic Cooperation and Development)
OM	Organic Matter
O&G	Oil and Grease, mg/L
O&M	Operation and Maintenance
p	Barometric pressure, kPa
psi	Pounds per square inch
P	Population of design, hab
P	Power, in HP or kW
P	Pressure, atm
PAR	Plug-flow anaerobic reactor or Piston anaerobic reactor
PF	Peak Factor
PFE_i	Percentage of "fresh" effluent during the last "i" days
PL	Power Level, kW/1000 m^3 or HP/1000 ft^3
PT	Primary treatment
P_x	Sludge Production in the reactor, kg/d
Q	Flow
Q_D	Design Average Flow of a WWTP
Q_{DH}	Design Hydraulic Flow of a WWTP
Q_{dom}	Flow of domestic WW
q	Per capita flow, L/hab · d
q_a	Hydraulic Load, Lps/m^2
q_{BOD_5}	Per capita BOD load, kg BOD_5/capita · d
q_{dom}	Domestic per capita flow, L/hab · d
q_F	Average Filtration Rate (m^3/m^2. d ≡ m/d)
q_{H_2O}	Hydraulic load in trickling filter, $m^3/m^2 \cdot h$
q_I	Infiltration, Lps/ha
Q_{DWW}	Flow of domestic WW
Q_I	Infiltration Flow, Lps
Q_{maxd}	Maximum daily flow, k_1Q_D
Q_{maxh}	Maximum hourly flow, $k_1k_2Q_D$