Stabilization Ponds in the Tropics: Promotion of the Sanitary Reuse of Water[1]

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This article reports the results of efforts by PAHO's Environmental Health Program to lay the groundwork for designing wastewater stabilization ponds suited to tropical areas. The resulting design concepts are flexible (permitting pond construction to be adapted to a broad range of terrains, community sizes, and working temperatures) and directed at meeting WHO standards established for the microbial quality of effluents used in agriculture and aquaculture.

The WHO standards (1) call for treated wastewater being used in agriculture or aquaculture to contain less than 1 000 fecal coliforms per 100 ml. The plans outlined here, which are calculated to meet those standards, seek to minimize the pond area and volume needed by using two high-load primary anaerobic ponds discharging into an elongated secondary pond with a length-to-width ratio of at least 15:1. In rough terrain the elongated pond can be allowed to meander, following the land's natural contours. However, where the terrain is level it is recommended that a system of partitions be used to maintain the 15:1 ratio for operating purposes while changing the actual ratio of the secondary pond's outer dimensions to something like 5:3.

Basic equations presented in the text will be helpful in estimating the pond sizes needed to cope with different climatic conditions, community sizes, per capita rates of wastewater generation, and per capita biochemical oxygen demands.

While these equations should prove of great assistance during initial planning and development of preliminary criteria, nothing in this article supplants the topographic and geotechnologic studies that will be needed in order to clearly determine what is feasible in any given case.

The climate of tropical countries constitutes a very valuable natural resource that expedites the campaign against water pollution if criteria and technologies adapted to the realities of that climate are employed.

Within the Region of the Americas, stabilization ponds have been used since the 1950s for treating wastewater of both industrial and domestic origin. Their efficiency in removing the pathogens this liquid waste contains has been confirmed by many studies, including studies carried out by the Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS) as part of PAHO's Environmental Health Program in the 1980s (2, 3).

Among other things, stabilization ponds produce effluents of adequate microbiologic quality without need of resorting to disinfection. These effluents, containing high concentrations of algae, are much appreciated by farmers for their high nutrient content, which makes it possible to save on fertilizer.

Experience accumulated over more than 30 years of evaluating the behavior of these ponds indicates they are very ef-

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ficient in tropical areas, where their typical cost is half to a quarter of that in temperate or colder zones. Moreover, other data and projects studied by the author in the early 1990s in Costa Rica, the Dominican Republic, and Mexico indicate that in the tropics the cost of treating a cubic meter of wastewater in stabilization ponds is only about a tenth of the cost of treating it in conventional plants (*4*).

Because of this strong assist provided by tropical conditions, it is vitally important that tropical regions not copy or impose upon themselves criteria and technologies developed for other climates.

For the purposes of this article we will consider stabilization ponds in tropical areas to be ones whose average water temperature during the coldest month of the year is 15 °C or higher.

USE OF WASTEWATER IN AGRICULTURE AND AQUACULTURE

In 1989 the World Health Organization (WHO) published *Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture* (*1*), which was translated into Spanish in 1991. These guidelines refer to the *use* of wastewater, both *direct use* and *indirect use* (in bodies of water such as rivers and lakes that are used for irrigation after receiving effluents). Among other things, the guidelines employ available epidemiologic evidence to establish that if wastewater is treated to a degree where the most probable number of fecal coliforms per 100 milliliters (MPN FC/100 ml) is less than 1 000 and the number of intestinal nematode eggs per liter is less than 1, the water can then be considered suitable for irrigation, even of food crops (*1*, see p. 44).

In this connection, it is worth noting the findings of studies carried out by PAHO's Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS) in Lima, Peru. These studies indicate that if primary, secondary, and sometimes tertiary ponds are used to achieve an effluent with a concentration of less than 1 000 FC/100 ml, the concentration of intestinal nematode eggs is reduced to zero (*5*).

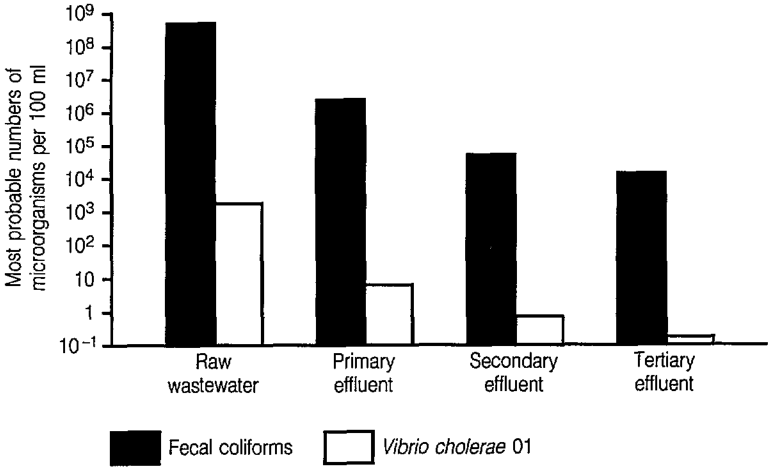
The WHO guidelines also discuss the criteria for a stabilization pond project designed to achieve the desired colimetry objective, it being understood that when this is accomplished, the objective regarding nematode egg levels will also have been achieved.

As indicated in Figure 1, studies carried out by CEPIS in June and July 1992 on stabilization ponds in San Juan de Miraflores, Lima, Peru, showed a decay rate of *Vibrio cholerae* 01 similar to that occurring with the fecal coliforms (*2*). (Similar correlations had already been found for the salmonellas and shigellas.) The CEPIS results coincide with those obtained by Kott and Betzer in 1972 and by Daniel and Lloyd in 1980 in Bangladesh. All of these results permit the interpretation that the decay constant (K_b) of *Vibrio cholerae* in stabilization ponds has an order of magnitude similar to that of the decay constant of the fecal coliforms in these ponds (*6*).

STABILIZATION POND DESIGN

By analyzing a great mass of data from studies and evaluations of stabilization pond behavior, the PAHO Environmental Health Program was able to define a mathematical model to facilitate prediction of effluent quality (*3*). Using this model, it was found that in tropical areas the necessary area and volume of the stabilization ponds could be minimized by using primary anaerobic ponds with a high load followed by elongated facultative ponds with a length-to-width ratio of at least 15:1.

Figure 1. Removal of fecal coliforms and *Vibrio cholerae* from wastewater by stabilization ponds in San Juan de Miraflores, Lima, Peru, in the winter (June–July) of 1991. The logarithmic chart shows the most probable numbers of microorganisms per 100 ml in raw wastewater entering the first pond and in effluent leaving the facility's primary, secondary, and tertiary ponds working in series.



Although the proposed design is directed at achieving an effluent with a particular concentration of fecal coliforms, in doing this it also removes from 80% to 90% of the biochemical oxygen demand (BOD). In general, the microbiologic quality of the effluent from such ponds is very good, for which reason it is expected that if such installations were widely used in tropical countries they would serve as a powerful tool for combating cholera and other diarrheal diseases transmitted by water.

Proposed Design Criteria

What is proposed is that wastewater of domestic origin be treated through discharge into two high-load primary anaerobic ponds operating in parallel, both of whose effluents pass into an elongated pond whose length-to-width ratio is 15:1. The usual depth for these ponds ranges from three to four meters for anaerobic ones and from two to three meters for facultative ones.

The Two Primary Anaerobic Ponds

These ponds will be square in shape, with a working depth (Z_{p1}) of four meters and an additional depth (Z_{p2}) for accumulation of sludge that will be removed every 2 years (that is, it will be removed alternately from one pond each year). The recommended surface load per unit area per day of use (i),[3] as well as the additional depth needed for sludge accumulation, will depend on the average water temperature during the coldest month of the year, in accordance with the figures shown in Table 1.

Paired primary ponds with the pro-

[3] i = rate of work, expressed as the 5-day biochemical oxygen demand (BOD_5) in kilograms per hectare per day.

Table 1. The influence of different average temperatures in the coldest month on stabilization pond variables i and Z_{p2} and elongated pond variable K_b. The variable i is rate of work—the five-day biochemical oxygen demand (BOD_5) in kilograms per hectare per day that can be accommodated by the primary anaerobic ponds; Z_{p2} is the additional stabilization pond depth needed, in meters; and K_b is the elongated pond's daily bacterial decay constant in days^{-1}.

	Primary anaerobic ponds		
Temperature (°C)	i (BOD_5 load in kg/ha/day)	Z_{p2} (additional depth, in meters)	Elongated pond bacterial decay constant in days^{-1} (K_b)
15	2 000	0.60	0.59
20	3 000	0.80	0.75
25	4 000	1.00	0.96
30	5 000	1.20	1.22

posed dimensions have the capacity to reduce the concentration of fecal coliforms by one power of 10. They will also condition the wastewater for its passage into the elongated facultative pond that receives their effluents.

These anaerobic ponds should be kept at least one kilometer away from any city and at least 500 meters from the nearest periurban dwelling. The odor that these ponds produce in tropical climates is comparable to that of an Imhof tank. The odor can be reduced by recycling the effluent from the elongated pond back to these primary ponds or by employing mechanical aeration.

The proper dimensions for these primary ponds can be obtained by solving the following equation:

$$W_p = 100 \times (y_c(P \div 2) \div i)^{1/2} \quad (1)$$

where

W_p = average length of a primary pond side (in meters)
y_c = per capita generation of 5-day biochemical oxygen demand (BOD_5) at 20 °C in g/day per capita
P = design population in thousands of inhabitants
i = rate of work (5-day biochemical oxygen demand [BOD_5] at 20 °C) for the average temperature of the water in the coldest month in kilograms/hectare/day.

For example, if y_c = 50 g/inhabitant/day, P = 10 (10 000 inhabitants), and i = 3 000 kg/ha/day, then

$$W_p \text{ (in meters)} = 100 \times (y_c(P \div 2) \div i)^{1/2}$$

$$W_p = 100 \times (50 \times 5 \div 3\,000)^{1/2}$$

$$W_p = 100 \times (250 \div 3\,000)^{1/2}$$

$$W_p = 100 \times (0.833)^{1/2}$$

$$W_p = 100 \times 0.289$$

$$W_p = 28.9 \text{ meters (see Table 1)}$$

For the values of "i" in Table 1 and a y_c value of 50 g per inhabitant per day, the dimensions shown in Table 2 are obtained.

The Elongated Secondary Pond

This pond, which receives the effluent from the primary ponds, is designed to work under the regimen of a "piston flow," a type of flow in which the wastewater entering the pond travels through it without mixing with the general mass

Table 2. The dimensions in meters (width of one side, W_p; working depth, Z_{p1}; and additional depth, Z_{p2}) of each of the two primary anaerobic ponds calculated using the temperatures and work rates (i values) shown in Table 1, a generated biological oxygen demand per inhabitant (y_c) of 50 g/inhabitant/day, and population (P) values for communities ranging from 2 000 to 100 000 inhabitants.

	Temperatures (°C) and i values (kg/ha/day)			
Population (P) in thousands	15 °C 2 000 kg/ha/day	20 °C 3 000 kg/ha/day	25 °C 4 000 kg/ha/day	30 °C 5 000 kg/ha/day
2	15.81 m	12.91 m	11.18 m	10.00 m
5	25.00 m	20.41 m	17.68 m	15.81 m
10	35.36 m	28.87 m	25.00 m	22.36 m
25	55.90 m	45.64 m	39.53 m	35.36 m
50	79.06 m	64.55 m	55.90 m	50.00 m
100	111.80 m	91.29 m	79.06 m	70.71 m
Z_{p1} (working depth)	4.00 m	4.00 m	4.00 m	4.00 m
Z_{p2} (additional depth)	0.60 m	0.80 m	1.00 m	1.20 m

of water in the pond. The pond's dimensions are indicated by the following formula:

$$N = N_o \left(e^{-(4/9)(V/Q)K_b}\right) \qquad (2)$$

where

- N = concentration of bacteria in the effluent leaving the elongated pond
- N_o = concentration of bacteria in the effluent entering the elongated pond
- e = a constant (approx. 2.71828), the base used in the Naperian (natural) system of logarithms
- V = volume of the elongated pond (in cubic meters)
- Q = rate of effluent flow into the elongated pond (in cubic meters per day)
- K_b = bacterial decay constant (day^{-1}); see Table 1 for the value of K_b at different temperatures.

See reference 3 for the justification of this formula,[4] and reference 7, pages 57–67, for justification of use of the factor 4/9.[5]

If the effluent from the elongated pond is to be reused directly (i.e., for irrigation), its concentration of fecal coliforms (FC) should be less than 1 000 FC/100 ml.

Suppose, for example, that raw wastewater with 10^9 FC/100 ml is purified 90% in the primary ponds, yielding an effluent leaving the primary ponds with 10^8 FC/100 ml. In that case, if the elongated pond's effluent contains 1 000 FC/100 ml,[6] the following condition holds:

$$N/N_o = 10^3/10^8 = 0.00001$$

[4]Formula (2) is the mathematical expression of Chick's Law for bacterial decay in a batch reactor.

[5]It is known that under laminar flow conditions in a wide rectangular channel the mean velocity of water is 2/3 of the maximum. This factor becomes 4/9 after taking into consideration lateral restrictions to this flow in an elongated pond.

[6]The WHO guidelines for stabilization pond effluent quality call for a concentration of less than 1 000 fecal coliforms per 100 ml. Accordingly, it is recommended that W_e (the average width of the elongated pond) be greater than the value yielded by equations (3) and (4) below.

From equation (2) we have:

$$\text{Log}_e (N/N_o) = -(4/9)(V/Q)K_b$$

$$\text{Log}_e (0.00001) = -(4/9)(V/Q)K_b$$

$$= -11.51293$$

$$V/Q = (9/4)(-11.51293)/K_b$$

$$V = 25.90408\ Q/K_b$$

In addition, if the pond has the configuration shown in Figure 2, with the minimum length-to-width ratio of 15:1 being created by use of two partitions, and if a depth of 2.5 meters is used, then

$$V = 2.5 \times 3W_e \times 5W_e$$

$$= 37.5 \times W_e^2 = 25.90408\ Q/K_b$$

$$W_e^2 = 0.69\ Q/K_b$$

$$W_e = 0.83\ (Q/K_b)^{1/2} \qquad (3)$$

where

W_e = average width of the elongated pond

K_b = bacterial decay constant (day^{-1}) for the average water temperature in the coldest month (see Table 1)

Q = average flow (m^3/day).

Also, $Q = qP$ where

q = wastewater flow in liters/inhabitant/day and

P = design population in thousands of inhabitants.

Therefore,

$$W_e = 0.83\ (qP/K_b)^{1/2} \qquad (4)$$

For example, if q (the average daily wastewater production per inhabitant) were 200 liters, P were 5 (for 5 000 inhabitants served), and the temperature were 30 °C (making the K_b constant 1.22, as in Table 1), then

$$W_e = (0.83)\ (200 \times 5/1.22)^{1/2}$$

$$W_e = 0.83 \times 28.63$$

$$W_e = 23.76 \text{ meters, and}$$

$$15W_e = 356.4 \text{ meters}$$

For an average per capita wastewater production (q) of 200 liters per day, the N_o value cited, a population of 2 000 to 100 000 inhabitants, and the temperature and K_b values shown in Table 1, the W_e values indicated in Table 3 are obtained. As this table and the foregoing account demonstrate, equations (1) and (4) make it possible to determine the relevant design dimensions of ponds suited to a broad range of differing situations very fast.

In rough terrain, the elongated secondary ponds can be allowed to meander, following the land's contour lines. However, where the terrain is level, construction of elongated ponds is very expensive; it is therefore suggested that a scheme with partitions be used, as in Figure 2.

Areas and Volumes Required

For each set of Table 2 and 3 values, Table 4 shows the required total area (in hectares) of all three ponds and the water volume all three would contain when full. Table 5 shows the pond area (in square meters) and pond volume (in cubic meters) required per capita in each case. Table 6 provides information about the minimum land area required at the site, both overall and per inhabitant served, taking into consideration the additional land required for dikes, access roads, and adequate separation of the ponds from neighboring land.

Figure 2. A design for the primary anaerobic ponds and elongated secondary pond suited to level or gently sloping terrain.

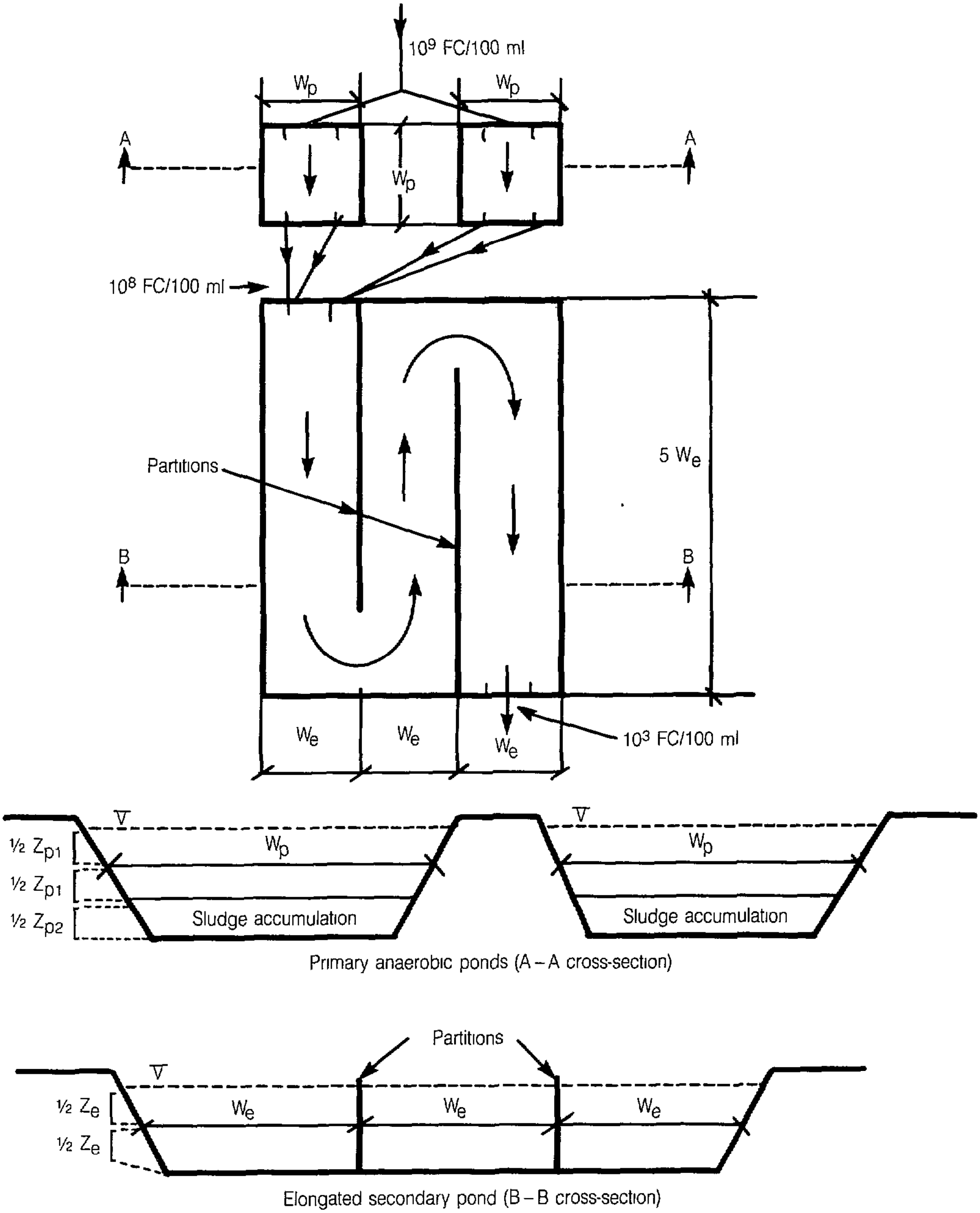


Table 3. Calculated values of W_e (the minimum width of the elongated pond) where the ratio of length to width is 15:1, the temperatures and bacterial decay constant (K_b) values are as shown in Table 1, the population served ranges between 2 000 and 100 000 inhabitants, the wastewater flow per inhabitant per day (q) is 200 liters, and the fecal coliforms in the entering and departing effluents (N_o and N), respectively, are 10^8/100 ml and 10^3/100 ml.

Population (P) in thousands	Temperatures (°C) and bacterial decay (K_b) values			
	15 °C, K_b = 0.59	20 °C, K_b = 0.75	25 °C, K_b = 0.96	30 °C, K_b = 1.22
2	21.61 m	19.17 m	16.94 m	15.03 m
5	34.17 m	30.31 m	26.79 m	23.76 m
10	48.32 m	42.86 m	37.88 m	33.61 m
25	76.41 m	67.77 m	59.90 m	53.14 m
50	108.06 m	95.84 m	84.71 m	75.14 m
100	152.82 m	135.54 m	119.80 m	106.27 m
Z_e (depth)	2.50 m	2.50 m	2.50 m	2.50 m

Table 4. Areas (hectares) occupied and volumes (thousands of cubic meters) held by ponds with the dimensions specified in Tables 2 and 3. These area and volume figures are for the set of all three ponds serving the indicated population at the indicated average cold-month temperature; the volume figures include the additional depth (Z_{p2}) in the stabilization ponds; y_c, q, K_b, N_o, and N are as specified in Tables 2 and 3.

Population (P) in thousands	Measure	Average cold month temperature (°C)			
		15	20	25	30
2	Area (ha)	0.75	0.58	0.46	0.36
	Volume (10^3 m^3)	19.81	15.38	12.01	9.51
5	Area (ha)	1.88	1.46	1.14	0.90
	Volume (10^3 m^3)	49.54	38.44	30.04	23.78
10	Area (ha)	3.75	2.92	2.28	1.79
	Volume (10^3 m^3)	99.07	76.89	60.07	47.55
25	Area (ha)	9.38	7.31	5.69	4.49
	Volume (10^3 m^3)	247.68	192.23	150.18	118.88
50	Area (ha)	18.76	14.61	11.39	8.97
	Volume (10^3 m^3)	495.36	384.45	300.35	237.75
100	Area (ha)	37.53	29.22	22.78	17.94
	Volume (10^3 m^3)	990.72	768.90	600.70	475.50

CONCLUDING REMARKS

The final design of a system of stabilization ponds can only be made after topographic and geotechnologic studies have been completed, since it is they, in the final analysis, that determine what is feasible. However, the equations and the tables presented here will be of great assistance with initial planning and in developing preliminary criteria. Further information on the theoretical bases involved and construction details is provided in references 3, 4, and 7.

Table 5. Areas (square meters) per inhabitant and volumes (cubic meters) per inhabitant of the pools listed in Table 4.

	Temperatures (°C) and bacterial decay (K_b) values			
	15 °C, K_b = 0.59	20 °C, K_b = 0.75	25 °C, K_b = 0.96	30 °C, K_b = 1.22
Area (m^2/inhabitant)	3.75	2.92	2.28	1.79
Volume (m^3/inhabitant)	9.91	7.69	6.01	4.76

Table 6. Land areas needed (total area in hectares and area per inhabitant in square meters) for each set of stabilization ponds listed in Table 4. L_t = total land area, L_I = area per inhabitant.

Population (P) in thousands	Land measure	Average cold month temperature (°C)			
		15	20	25	30
2	L_t (ha)	1.65	1.39	1.20	1.04
	L_I (m^2/inhabitant)	8.23	6.97	5.98	5.21
5	L_t (ha)	3.16	2.60	2.17	1.84
	L_I (m^2/inhabitant)	6.31	5.21	4.34	3.68
10	L_t (ha)	5.47	4.44	3.64	3.03
	L_I (m^2/inhabitant)	5.47	4.44	3.64	3.03
25	L_t (ha)	11.96	9.57	7.71	6.31
	L_I (m^2/inhabitant)	4.78	3.83	3.09	2.52
50	L_t (ha)	22.31	17.72	14.15	11.45
	L_I (m^2/inhabitant)	4.46	3.54	2.83	2.29
100	L_t (ha)	42.44	33.52	26.58	21.35
	L_I (m^2/inhabitant)	4.24	3.35	2.66	2.13

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[7]The references published by CEPIS (2, 4, 5, and 7) may be obtained by writing to the Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS), Casilla Postal 4337, Lima 100, Peru—FAX No. (5114) 378-289.