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The carbon-sequestration potential of municipal wastewater treatment

Diego Rosso *, Michael K. Stenstrom

University of California, Los Angeles, Civil and Environmental Engineering Department, 5714 Boelter Hall, Los Angeles, CA 90095-1593, USA

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Abstract

The lack of proper wastewater treatment results in production of CO_2 and CH_4 without the opportunity for carbon sequestration and energy recovery, with deleterious effects for global warming. Without extending wastewater treatment to all urban areas worldwide, CO_2 and CH_4 emissions associated with wastewater discharges could reach the equivalent of $1.91 \times 10^5\ t_{CO_2}\ d^{-1}$ in 2025, with even more dramatic impact in the short-term. The carbon sequestration benefits of wastewater treatment have enormous potential, which adds an energy conservation incentive to upgrading existing facilities to complete wastewater treatment. The potential greenhouse gases discharges which can be converted to a net equivalent CO_2 credit can be as large as $1.21 \times 10^4\ t_{CO_2}\ d^{-1}$ by 2025. Biomass sequestration and biogas conversion energy recovery are the two main strategies for carbon sequestration and emission offset, respectively. The greatest potential for improvement is outside Europe and North America, which have largely completed treatment plant construction. Europe and North America can partially offset their CO_2 emissions and receive benefits through the carbon emission trading system, as established by the Kyoto protocol, by extending existing technologies or subsidizing wastewater treatment plant construction in urban areas lacking treatment.

This strategy can help mitigate global warming, in addition to providing a sustainable solution for extending the health, environmental, and humanitarian benefits of proper sanitation.

Keywords: Biogas; Carbon sequestration; Energy recovery; Global warming; Greenhouse gases; Wastewater

1. Introduction

Global warming is an alarming phenomenon that was recognized as early as 1975 by measuring increasing temperature trends over the past two millennia (Broecker, 1975; Mann and Jones, 2003; Mann et al., 2003). Numerous sources are reporting impacts of global warming such as increasing instances of atmospheric instabilities (e.g.: Tett et al., 1999), which are creating major concerns on an international level. Nevertheless, sceptic comments regarding future projections of global warming effects exist outside the scientific community (Lomborg, 2001). The reason for the accelerated increase of global temperature in the past 60 years has being attributed largely to anthropogenic greenhouse gas (GHG) emissions (Tett et al., 1999). The Kyoto protocol sets an emission limit for the six GHG with highest global warming potential. Their emission rates are to be reduced by at least 6% by 2008 as compared to 1990. Thus, the protocol establishes a trading system for carbon emission credits, with a current market value for CO_2 emissions in the range of USD 15–25 t^{-1} (Greenfield and Batstone, 2005). One of the carbon emission sources derives from the lack of wastewater treatment, which is equivalent to the discharge of the carbon contaminating the wastewater in the environment.

In the year 2000, 2.8 billion people lived in urban areas worldwide, and 400 million (14%) did not have access to "improved" sanitation (WHO/UNICEF, 2000), which is defined as a system where "excreta are disposed of in such a way that they reduce the risk of fecal-oral transmission to its users and the environment" (UNDP, 2005). Improved sanitation may imply only conveyance systems (e.g., sewers) and not wastewater treatment. In order to distinguish

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* Corresponding author. Tel.: +1 310 825 1408; fax: +1 310 206 2222.
E-mail address: bidui@ucla.edu (D. Rosso).

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between those served locations that have or do not have wastewater treatment, we introduce the term "sewered" to mean those areas which have collections to segregate wastewaters to reduce human exposure and "fully treated" for those areas with collection systems and secondary treatment plants. Using these two definitions an approximation can be made to estimate sewered and fully treated areas, which is needed because the available census documents only the presence of sewers. During our careers we have visited numerous urban areas worldwide where "improved" sanitation corresponded to full wastewater treatment and, with some exceptions, they were all located in Europe, North America, and Japan. In our calculation Japan is grouped within Asia, i.e. without proper treatment, in spite of their well developed treatment plants. This does not bias the final result since there exist urban areas in the world outside Europe and North America where full biological wastewater treatment is practiced (e.g., Singapore), but are not as large as Japan's population. One of the United Nations Millennium Development Goals is to increase the level of sanitation by 2015 so that only 8% of the worldwide population is without access to improved sanitation. This task is challenging if we consider that world urban population in 2015 is projected to be 3.8 billion, 1 billion more than in 2000 (WHO/UNICEF, 2000).

Proper treatment sequesters carbon as inert biomass, recovers biogas energy which can defray treatment costs, and avoids uncontrolled carbon discharge, thus reducing carbon released to the atmosphere (Cakir and Stenstrom, 2005; Monteith et al., 2005). Biomass disposal in confined landfills creates a net carbon sink, with little opportunity to return to the atmosphere in any foreseeable time-span because the biomass is largely devoid of methane forming potential due to prior digestion in the treatment plant (Pohland and Al-Yousfi, 1994). Biogas energy recovery is a renewable and economically viable substitute for energy production which could otherwise be met through fossil fuels. Due to the presence of inert CO_2, biogas has lower combustion temperatures which reduce the generation of NOx, which is also an advantage. Furthermore, inert gases retain the heat of combustion in the form of sensible heat, which can be recovered in heat exchangers.

The contaminants present in domestic wastewater in urban areas arise not only from human faecal material, but also from synthetic sources (30–50%) such as chemicals from petrochemical industries and therefore they cannot be considered a renewable source of carbon (Gray, 2004). These contaminants are in the form of detergents and surfactants and oil and grease, which are introduced not only as personal care products and household detergents, but also from industries that discharge pre-treated wastewaters to municipal treatment systems. For example, in the City of Los Angeles, only one industry (a petroleum oil refinery) discharges through its own treatment plant and permit. All other industries, which include several other refineries and chemical industries, pretreat and discharge to publicly owned treatment plants. This is common practice in other US cities and large metropolitan areas, worldwide. In countries where food waste is disposed through sewers (as in the United States, for example) the percentage of non-renewable carbon in the wastewater maybe lower, but outside those regions there may be variation. Furthermore, cultural and economic needs in underdeveloped areas may encourage reuse of food considered waste in developed countries. In this paper, we do not quantify the origin of wastewater contaminants, but show the potential benefits of sequestration of the carbon present in wastewater independently from its origin.

In this paper, we show the benefits for global warming mitigation associated with proper wastewater treatment. The driving force that traditionally has promoted wastewater treatment is the removal of: carbon-, nitrogen-, and phosphorous-contaminants; bacteria and viruses; anthropogenic and endocrine disruptive compounds. Additional advantages are biomass stabilization/segregation, and biogas energy recovery. These last two play a crucial role as global warming mitigation factors. We show how these advantages can be quantified and we propose a strategy for developed countries to partially offset their carbon emissions. For the purpose of this paper, we quantified only energy and mass fluxes concerning treatment operations, as the treatment plant construction is too site specific to be generally quantified. Finally, we ignore the notion that carbon from biogenic sources is sustainable and does not contribute to the greenhouse effect. The sequestration of carbon from sustainable sources may reduce the rate of warming and partially avoid the positive feedback mechanisms that may trigger large temperature increases. Even if carbon sequestration only lasts for 50 years, the reduction is still valuable because of its retardation on the emission cycle.

2. Methods

To quantify the equivalent CO_2 emissions of wastewater treatment in large urban areas, we gathered data on urban population with access to improved sanitation for each continent (WHO/UNICEF, 2000). Table 1 shows data from 1990 and 2000, and projected data for 2015 and 2025. The projected data show a targeted increase of urban population with access to improved sanitation from 86% to 92% and 100%, respectively. The difference in percentages may appear small, but we must observe that between 2000 and 2025 the world urban population may increase by 60% (from 2442 million in 2000 to 4536 million in 2025; WHO/UNICEF, 2000).

Using the WHO/UNICEF datasets, we calculated energy and mass fluxes for wastewater treatment with biological nutrient removal (BNR). Fig. 1 shows a layout of the process, which is the activated sludge layout with lowest specific energy consumption (Rosso and Stenstrom, 2005). We assumed in order: headworks, primary clarifiers, modified Ludzack-Ettinger biological treatment, secondary clarifiers; anaerobic treatment of the sludge. Small fluxes of

Table 1
Summary of Actual and potential energy and mass emissions and offsets (1990–2025)

	Year	Urban wastewater		CO_2 production		CH_4 production		Biomass production		CH_4 energy recovery		Gross CO_2 emissions (10^3 t d^{-1})	Total CO_2 offsets (10^3 t d^{-1})	Net CO_2 emissions (10^3 t d^{-1})
		Sewered (10^6 m^3 d^{-1})	Unsewered (10^6 m^3 d^{-1})	Sewered (10^3 t d^{-1})	Unsewered (10^3 t d^{-1})	Sewered (10^3 t d^{-1})	Unsewered (10^3 t d^{-1})	Sewered (10^3 t_{VSS} d^{-1})	Unsewered (10^3 t_{VSS} d^{-1})	Sewered (TJ d^{-1})	Unsewered (TJ d^{-1})			
Africa	1990	16.7	2.95	1.65	0.29	0.20	0.04	1.16	0.20	5.29	0.93	3.03	−2.63	0.40
	2000	25.1	4.43	2.48	0.44	0.30	0.05	1.74	0.31	7.95	1.40	4.55	−3.96	0.59
	2015‡	46.2	4.02	4.57	0.40	0.56	0.05	3.20	0.28	14.6	1.27	7.22	−7.28	−0.06
	2025‡	67.3	0	6.65	0	0.81	0	4.66	0	21.3	0	8.89	−10.6	−1.71
Asia	1990	138	68.0	9.52	4.69	1.11	0.55	6.35	3.13	29.0	14.3	25.1	−14.4	10.7
	2000	211	59.5	14.6	4.10	1.70	0.48	9.71	2.74	44.4	12.5	30.2	−22.1	8.14
	2015‡	346	42.8	23.9	2.95	2.78	0.34	15.9	1.97	72.7	8.99	39.4	−36.2	3.21
	2025‡	477	0	32.9	0	3.84	0	22.0	0	100	0	43.5	−50.0	−6.48
Latin America and Caribbean	1990	40.1	7.07	2.76	0.49	0.32	0.06	1.84	0.33	8.42	1.49	4.95	−4.19	0.76
	2000	51.0	7.62	3.52	0.53	0.41	0.06	2.35	0.35	10.7	1.60	6.05	−5.34	0.72
	2015‡	70.7	5.32	4.87	0.37	0.57	0.04	3.25	0.24	14.9	1.12	7.42	−7.39	0.02
	2025‡	85.8	0	5.92	0	0.69	0	3.95	0	18.0	0	7.81	−8.98	−1.16
Oceania	1990	2.70	0.03	0.146	0.001	0.02	0	0.09	0.00	0.42	0.004	0.19	−0.21	−0.02
	2000	3.15	0.03	0.170	0.002	0.02	0	0.11	0.00	0.49	0.005	0.23	−0.25	−0.02
	2015‡	3.83	0.04	0.207	0.002	0.02	0	0.13	0.00	0.60	0.006	0.28	−0.30	−0.02
	2025‡	4.50	0	0.243	0	0.03	0	0.15	0	0.71	0	0.32	−0.35	−0.03
Europe	1990	131	0	7.05	0	0.78	0	4.48	0.00	20.5	0	9.20	−10.2	−1.00
	2000	134	2.74	7.25	0.15	0.81	0	4.61	0.09	21.1	0.43	9.85	−10.5	−0.65
	2015‡	140	1.42	7.58	0.08	0.84	0	4.82	0.05	22.0	0.22	10.1	−11.0	−0.87
	2025‡	143	0	7.71	0	0.86	0	4.90	0	22.4	0	10.1	−11.2	−1.09
North America	1990	85.2	0	5.88	0	0.68	0	3.92	0	17.9	0	7.76	−8.92	−1.16
	2000	95.6	0	6.59	0	0.77	0	4.40	0	20.1	0	8.71	−10.0	−1.30
	2015‡	111	0	7.67	0	0.89	0	5.11	0	23.4	0	10.1	−11.6	−1.51
	2025‡	121	0	8.36	0	0.97	0	5.57	0	25.5	0	11.0	−12.7	−1.65
Global	1990	413	78.0	27.0	5.47	3.12	0.64	17.8	3.66	81.5	16.7	50.3	−40.6	9.68
	2000	520	74.3	34.6	5.22	4.00	0.61	22.9	3.49	105	16.0	59.6	−52.1	7.49
	2015‡	718	53.6	48.8	3.79	5.67	0.44	32.4	2.54	148	11.6	74.5	−73.8	0.77
	2025‡	899	0	61.8	0	7.20	0	41.2	0	188	0	81.6	−93.7	−12.1

Assumptions: MCRT = 15 d; nitrification/denitrification; influent N–NH_4 = 20 mg l^{-1}; SRT_{dig} = 30 d; biogas = 65% CH_4 + 35% CO_2; biogas energy content = 38.5 kJ m^{-3}; digestion yield = 0.75 m^3_{biogas} kg^{-1}_{VSS}; biomass destruction rate = 50%. *Key:* MCRT, mean cell retention time; SRT_{dig}, sludge retention time in digester; VSS, volatile suspended solids; ‡ = estimate. Regional assumptions: Africa (100 l p^{-1} d^{-1}, 300 mg_{BOD} l^{-1}); Asia (200 l p^{-1} d^{-1}, 200 mg_{BOD} l^{-1}); Latin America and Caribbean (150 l p^{-1} d^{-1}, 200 mg_{BOD} l^{-1}); Oceania (150 l p^{-1} d^{-1}, 150 mg_{BOD} l^{-1}); Europe (250 l p^{-1} d^{-1}, 150 mg_{BOD} l^{-1}); North America (400 l p^{-1} d^{-1}, 200 mg_{BOD} l^{-1}).

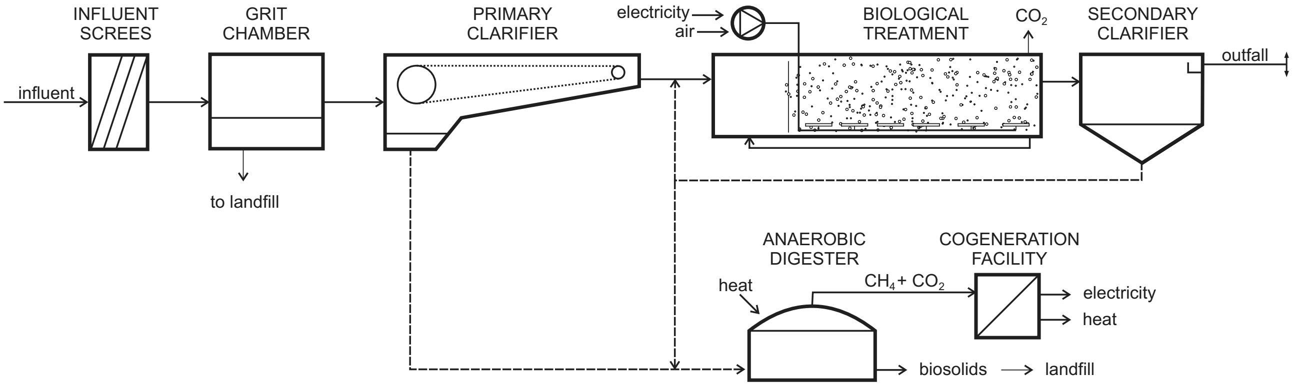

Fig. 1. Layout of a typical municipal wastewater treatment plant. This was used as basis for our calculations for mass end energy fluxes.

energy and GHG exist for head works and clarifiers, but are negligible (Reardon, 1995; Monteith et al., 2005). Our calculations are divided into equivalent CO_2 emissions and offsets. The net effect is the sum of the two. Also, we assume no N_2O production.

2.1. Calculation of equivalent carbon dioxide emissions

Carbon- and nitrogen-substrate oxidation is described by:

$$\text{C-substrate} + \text{N-substrate} + O_2 \rightarrow CO_2 + C_5H_7NO_2 + H_2O \quad (1)$$

Eq. (1) shows that the elimination of C-substrate yields to production of CO_2 and partial segregation of carbon as biomass ($C_5H_7NO_2$; Metcalf and Eddy, 2003). This is the first global warming mitigation benefit offered by wastewater treatment. Biomass digestion produces CH_4 and stabilised biomass following the reaction:

$$\text{Active biomass} + \text{C-substrate} \rightarrow CH_4 + CO_2 + \text{stabilised biomass} + H_2O \quad (2)$$

Typically, the biogas ($CH_4 + CO_2$) is either flared or refined for further utilization in power generation units. The stabilised biomass can be sent to landfills, if available, land application, or incinerated. Eq. (2) shows the other global warming mitigation benefit associated with wastewater treatment: the energy recovered by burning the biogas. The mitigation benefit goes beyond CH_4 energy recovery, as the energy production eliminates discharge of CH_4, which has a severely worse effect on global warming than CO_2 (IPCC, 2001). Methane production, in theory, is just an intermediate step before final discharge of CO_2 to the atmosphere. If the combustion

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (3)$$

is performed in a power generation unit, the equivalent CO_2 emissions w_{biogas} are:

$$w_{\text{biogas}}^{\text{comb}} = \frac{2.75\ \text{kg}_{CO_2}}{\text{kg}_{CH_4}} \quad (4)$$

We calculated the energy recovery associated with the increase in urban population served by improved sanitation in 2015 and 2025. This spreadsheet contains detailed forms of Eqs. (1) and (2), and a detailed wastewater treatment plant design algorithm.

The equivalent CO_2 emission associated with biological aerobic treatment ($\dot{m}_{CO_2}^{\text{resp}}$) is the CO_2 production due to Eq. (1). The emissions of uncombusted CH_4 ($\dot{m}_{CH_4}^{\text{emitted}}$) and the CO_2 emitted ($\dot{m}_{CO_2}^{\text{comb}}$) after biogas energy recovery (Eq. (3)) have to be added to calculate the total equivalent CO_2 emissions ($\dot{m}_{CO_2}^{\text{emissions}}$). The sum of CO_2 emissions from the aerobic biological treatment ($\dot{m}_{CO_2}^{\text{resp}}$) and CO_2 emitted in the biogas combustion ($\dot{m}_{CO_2}^{\text{comb}}$) is defined as the gross CO_2 emissions ($\dot{m}_{CO_2}^{\text{gross}}$). Since the emitted CH_4 decays over time, a time-horizon must be assumed. Typically, the assumed time-horizon is 100 year, and in order to be consistent with the current literature, for the CH_4 fugitive emissions, we used a mass conversion factor (IPCC, 2001):

$$w_{CH_4}^{\text{emitted}} = \frac{23\ \text{kg}_{CO_2}}{1\ \text{kg}_{CH_4}} \quad (5)$$

Since the impact of methane on the total emissions is heavily dependent on this parameter, an analysis of different time-horizons is reported in the discussion.

The CO_2 total equivalent emissions are therefore:

$$\dot{m}_{CO_2}^{\text{emissions}} = \dot{m}_{CO_2}^{\text{gross}} + w_{CH_4}^{\text{emitted}}\ \dot{m}_{CH_4}^{\text{emitted}} + w_{\text{biogas}}^{\text{comb}}\ \dot{m}_{CH_4}^{\text{comb}} \quad (6)$$

2.2. Calculation of equivalent carbon dioxide offsets

The carbon segregation associated with biomass production can be quantified with the endogenous respiration equation (Metcalf and Eddy, 2003):

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + NH_3 + 2H_2O \quad (7)$$

Eq. (7) concludes that for each mol of biomass ($C_5H_7NO_2$) reacting, 5 mol of CO_2 are segregated. In mass terms, the carbon sequestration potential associated with biomass production w_{biomass} is:

$$w_{\text{biomass}} = \frac{1.95\ \text{kg}_{CO_2}}{\text{kg}_{\text{biomass}}} \quad (8)$$

The total CO_2 offsets are the sum of the segregated biomass and of the equivalent CO_2 that would have been emitted if the biogas energy recovered were produced with fossil fuels ($\dot{m}_{CO_2}^{\text{energy offset}}$):

$$\dot{m}_{CO_2}^{\text{offsets}} = w_{\text{biomass}}\ \dot{m}_{\text{biomass}} + \dot{m}_{CO_2}^{\text{energy offset}} = w_{\text{biomass}}\ \dot{m}_{\text{biomass}} + e_{\text{bg}} \frac{\eta_{\text{ff}}}{h_{\text{ff}}} \tag{9}$$

where e_{bg} is the recovered biogas energy, η_{ff} is the efficiency of another power generation unit that produces the same energy as e_{bg} is the with fossil fuels and h_{ff} is the calorific value of the fossil fuel.

We assumed η_{ff} as 75% but its value is site specific and may vary (Sahely et al., 2006). We also assumed 50% losses in the value of the combusted gases in order to account for the upstream cleanup. This value is also site specific and is conservative, in our experience.

2.3. Calculation of net equivalent carbon dioxide emissions

The net, effective CO_2 production $\dot{m}_{CO_2}^{\text{net}}$ is then:

$$\dot{m}_{CO_2}^{\text{net}} = \dot{m}_{CO_2}^{\text{emissions}} - \dot{m}_{CO_2}^{\text{offsets}} \tag{10}$$

which, in this case, is

$$\dot{m}_{CO_2}^{\text{net}} = \dot{m}_{CO_2}^{\text{gross}} + w_{\text{equiv}}\ \dot{m}_{CH_4}^{\text{emitted}} + w_{\text{biogas}}^{\text{comb}}\ \dot{m}_{CH_4}^{\text{comb}} - w_{\text{biomass}}\ \dot{m}_{\text{biomass}} - \dot{m}_{CO_2}^{\text{energy offset}} \tag{11}$$

Results calculated with Eq. (11) are reported in Table 1 and as scenarios in Fig. 2. All negative values are credits which are biomass segregation and methane energy recovery (Eqs. (2) and (5)), and offset the CO_2 production by bacterial respiration and methane combustion (Eqs. (1) and (3)).

3. Results and discussion

Our results assume that all sewered areas perform secondary treatment with BNR, full energy recovery in a cogeneration facility and biomass sequestration. BNR will be valuable in urban areas where water quality may be impacted, but if the treated wastewaters can be reclaimed for agriculture, the analysis could be modified excluding nutrient removal. Table 1 shows the results of our calculations for sewered and unsewered areas.

Fig. 2 shows the worldwide emission/credit scenarios for levels of treatment outside Europe and North America ranging from 0% to 100%. If we consider the UN projected population growth and without any improvement of the current situation, the equivalent CO_2 daily discharge may reach 191 kt_{CO_2} d^{-1} in 2025. Note the extremely large difference between the 0% and 100% boundaries (worst and best scenarios, respectively). By 2025, the worldwide equivalent CO_2 flux could be -12.1 kt_{CO_2} d^{-1} (negative, hence a credit), mainly because Asia has the potential of doubling its own credit. The most likely current scenario is shown by the shaded area which, without improvement of the current situation, is very close to the worst scenario.

A detailed plot of the emissions outside Europe and North America, with the current situation, is plotted in Fig. 3. The boxes in this plot have 25% of wastewater treatment as upper boundary, and 0% as lower boundary. The disproportion between Asia and all other continents added together is large, and requires a non-linear scale for clarity

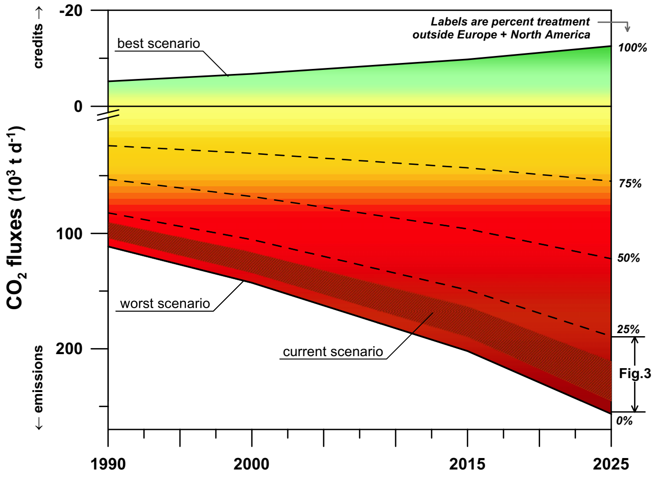

Fig. 2. Current and possible scenarios for CO_2 fluxes from urban wastewater treatment. On the vertical axis are CO_2 credits (−) and emissions (+). Labels (on the far right) show the percent treatment outside Europe + North America (where treatment is already 100%). The most likely current scenario is between 0% and 25% of treatment outside developed countries. The most optimistic projection is to approach the top of the graph (100%). Without any improvement of the current situation, the worldwide net CO_2 emissions due to lack of wastewater treatment may be between 150 and 191 kt_{CO_2} d^{-1} by 2025 (in detail in Fig. 3).

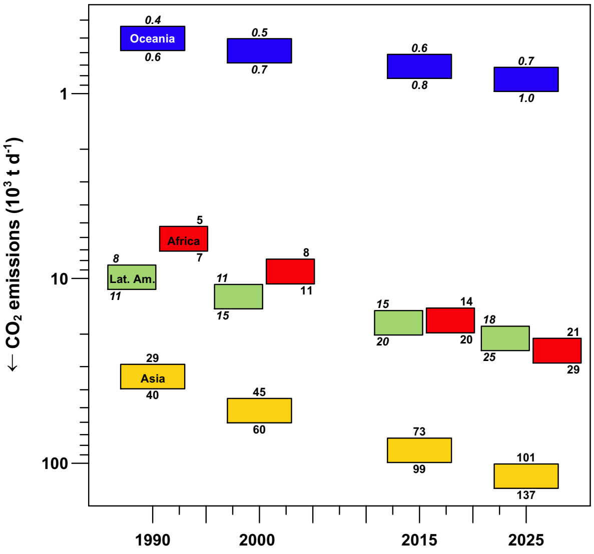

Fig. 3. CO_2 emissions from urban wastewaters outside Europe + North America: current scenario. The upper and lower boundaries of each box in the plot correspond to 25% and 0% treatment, respectively. This is the range containing the most likely current scenario which, with no improvement, is the most likely future scenario. Labels are emissions in equivalent kt_{CO_2} d^{-1}.

of graphing. If wastewater treatment is implemented in all urban areas of Asia alone, the worldwide balance would be in significant credit. If in the year 2000 all urban areas of Asia alone performed full biological wastewater treatment, the total CO_2 credits from wastewater treatment worldwide will approximately double.

Fig. 4 shows the biomass production and biogas recovery in equivalent kt_{CO_2} d^{-1}. In the period 1990–2025, Asia's production outnumbers the other continents combined, while tripling its absolute value. In each bar plot, the coloured area represents the biomass production, and the outlined area the biogas recovery. The shaded black areas represent the most likely current scenario for recovery in each continent, which for Europe and North America approaches completion. It is important to sequester the carbon in the biomass for this strategy to be successful. Approximately 3/4 of the carbon sequestration potential occurs because of biosolids sequestration and only 1/4 comes from energy production from biogas. Therefore, treatment strategies that do not sequester the carbon in the biosolids (i.e., land farming of the biosolids where they are degraded in 2–3 years, or biosolids incineration that requires additional fuel) will not result in a net GHG reduction. Biosolids disposal strategies that sequester the carbon for limited periods (20 years or more) may still be beneficial since they may delay return of carbon to the atmosphere, providing time for other GHG reduction strategies to become effective.

Fig. 5 shows the potential biogas energy recovery in 10^{12} J d^{-1}. Due to the magnitude of its urban population growth, Asia has the highest energy recovery potentials, followed by Africa and Latin America. For each graph, the solid lines show the urban population with access to improved sanitation (labels in million people). In each bar plot, the non-coloured area (top of the bar) corresponds to the energy that could be recovered if those urban areas were served by improved sanitation, but at the moment cannot benefit of any recovery. As the Millennium Development Goals indicate, the bar disappears in 2025, for all urban areas worldwide will be served by improved sanitation. The solid coloured areas in each bar plot represent the potential recovery that can already be achieved, if the full wastewater treatment and methane energy recovery were added to improved sanitation. The dark area in each bar plot is the most likely scenario without any improvement over the current situation, i.e. with full treatment and biogas energy fully recovered in Europe and North America, and almost no treatment and recovery elsewhere.

Wastewater treatment is and should be considered a global warming mitigation factor. Without proper treatment, the carbon in discharged wastewater will eventually enter the ecosystem as CH_4 (or CO_2), without the potentials for offset associated with biomass segregation and biogas energy recovery. We assume that all untreated wastewater is degraded anaerobically, yielding 50% CO_2 and 50% CH_4. Even in the event of no biomass segregation (e.g., where biomass is incinerated), the energy recovery associated with methane recovery is an advantageous benefit, which should always be considered when the methane production is significant. In our experience, in North America and Europe, methane is combusted in a power/steam generation facility when the plant is large (depending on site-specific conditions, with threshold sizes from 7500 to 110000 m^3 d^{-1}) and is flared or used only for heat generation (i.e., anaerobic digester heating, building heating, etc.) when the plant is smaller. In both cases no methane is discharged to the

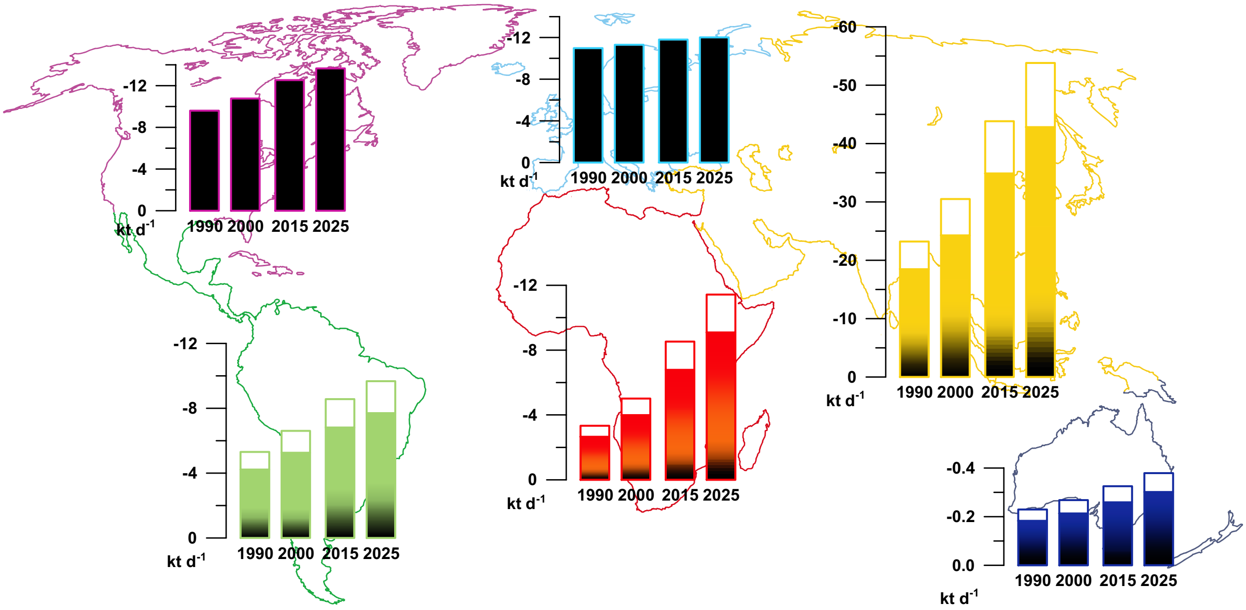

Fig. 4. Biomass production and biogas recovery in equivalent $kt_{CO_2}d^{-1}$. For each bar, the top outlined area is the carbon offset by biogas recovery; the solid coloured area is the carbon sequestered by biomass conversion; the black area is the amount of carbon most likely to be offset today.

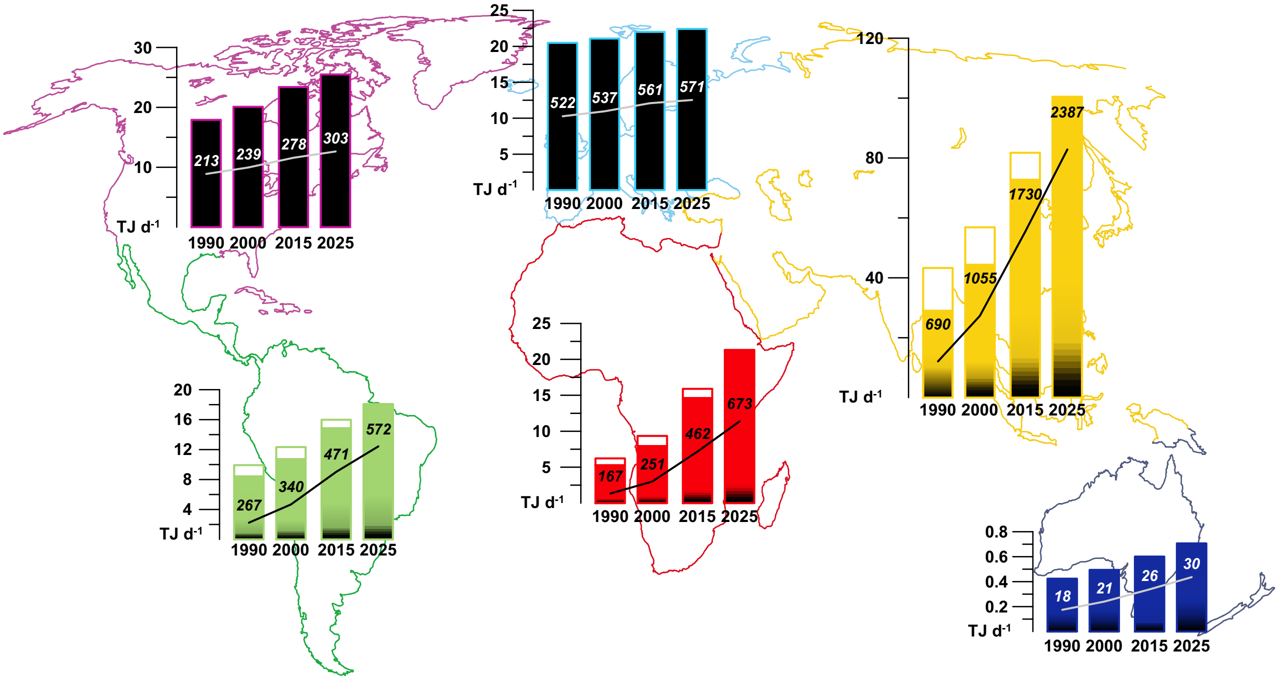

Fig. 5. Currently and potentially achievable biogas energy recovery in 10^{12} J d^{-1}. In each bar plot, the solid coloured areas represent the recovery that can already be achieved, if full wastewater treatment and methane energy recovery were added to improved sanitation. The dark area in each bar plot is the most likely scenario without any improvement over the current situation, i.e. full treatment and biogas energy fully recovered in Europe + North America, and almost no treatment/recovery elsewhere. Line plots are urban population served by improved sanitation (labels in million people).

atmosphere other than fugitive emissions or methane dissolved in liquid waste streams (thus reducing the greenhouse impact), with the additional advantage that larger wastewater treatment plants recover energy (with further reduction of greenhouse impacts). In any case, to reduce greenhouse impacts no methane should be discharged to the atmosphere.

The CH_4 weighing parameter ($w_{CH_4}^{emitted}$) has an important effect on the forecast of emission scenarios. In the current literature, the time-horizon of 100 years is typically adopted, corresponding to a value of 23 for $w_{CH_4}^{emitted}$ (IPCC, 2001). We calculated the net equivalent CO_2 emissions without improvement of the current situation with different values for $w_{CH_4}^{emitted}$ (Fig. 6). The results are dramatically different when choosing different time-horizons. The horizons chosen for this sensitivity analysis were 20 years, 100 years, and 500 years (with values for $w_{CH_4}^{emitted}$ of 62, 23, and 7 $\mathrm{kg_{CO_2}\,kg_{CH_4}^{-1}}$, respectively). Forecasting models for economic impact of mitigation measures used 20 or 30 years time-horizons (IPCC, 1999). In the short-term, i.e. when the mitigation is immediately needed, the effect of methane discharge is several times worse. It is important to distinguish between the time-span of methane release/recovery and biomass sequestration. Methane decays in the atmosphere in a scale of centuries, whilst biomass can be segregated immediately and perpetually or at least for lengthy periods of time. Therefore, the effective benefits of segregating biomass in the short-term are higher, and are more useful to curb the short-term effective CO_2 emissions (407 $\mathrm{kt_{CO_2}}$ d^{-1} with 20 years horizon, vs. 191 $\mathrm{kt_{CO_2}}$ d^{-1} with 100 years horizon).

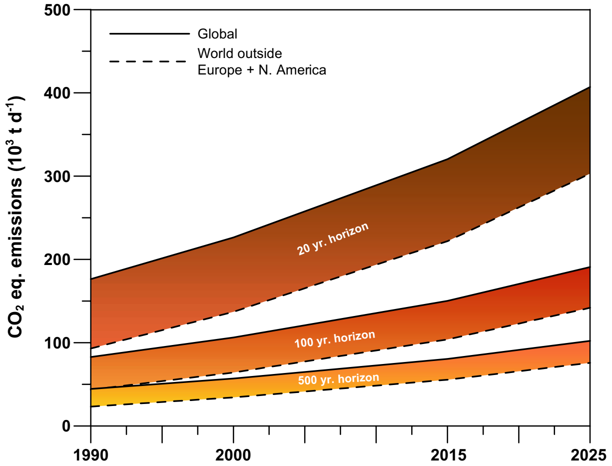

Fig. 6. Effect of the CH_4 global warming potential on the equivalent CO_2 emissions. When converting CH_4 to equivalent CO_2 emissions in a 20 years time span (most immediate effect) we observe the dramatic need for immediate measures. In the long term (500 years – horizon), CH_4 will decay and not have as a significant impact.

Presently the emphasis on green house gas emissions is concentrated on non-biogenic sources, and in this paper we show that there are significant opportunities to curb emissions from both non-biogenic and biogenic sources. This may become more important in the short term as more is learned about positive feed-back mechanisms and the need to quickly reduce GHG emissions. The notion that only non-biogenic sources are important has been discussed in greater depth by Monteith et al. (2005), and they note that the IPCC's (2000) calculation methods are most appropriate on a large scale, such as national inventories, and in need of improvement for end-users wishing to make abatement decisions.

4. Strategy for carbon trading

We propose a strategy that developed countries could adopt to exchange carbon credits with countries without full wastewater treatment and/or energy recovery. The traditional driving force for the treatment in developed areas is public health and environmental preservation. All these benefits could be exported to developing countries, and can be advantageous for both parties, since the developed countries can obtain carbon emission credits (the emission that the developing country would cause by not performing wastewater treatment) in exchange for exporting wastewater treatment technologies. The receiving urban area would receive public health, environmental, as well as economic benefits (the recovered energy remains in the area, reducing the local need of fossil fuel, and with additional improvements for the fishing and tourism industries).

Equivalent CO_2 emissions from urban wastewater treatment in underdeveloped countries amount to 1.4% of the non-fossil fuel related emissions. Since no country experiences a shortage of wastewater, this strategy for trading (or, better, exchanging) is applicable to all countries. Countries that have ratified the Kyoto protocol have an additional compelling motive. Performing full wastewater treatment in all urban areas worldwide has substantial economic incentives, but is also a necessity and an obligation towards the sustainable management of the global environment.

5. Conclusions

Proper wastewater treatment reduces greenhouse gases emissions and should be considered a global warming mitigation factor. Full wastewater treatment with biomass sequestration and biogas energy recovery can be a net carbon sequestration process. Currently, the worldwide scenario is close to the worst possible, but has large margin of improvement, if wastewater treatment is performed in urban areas with sewers.

Our data analysis projects global warming benefits in urban areas not served by improved sanitation, and quantifies the actual benefits enjoyed by urban areas already served. The potential of extending full wastewater treatment to urban areas lacking treatment is enormous, as shown by our results, and is equivalent to trading emission credits. By exporting treatment technologies and subsidizing construction to underdeveloped countries, for example, developed countries could partially offset their CO_2 emissions, in addition to extending ecological, humanitarian, and economical benefits.

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J. MARSHALL

Megacity, mega mess...

The creaking infrastructure of Indonesia's capital is overwhelmed by people, vehicles and pollution. As urbanization gathers pace across the developing world, **Jessica Marshall** visits Jakarta to witness its stomach-churning consequences.

On the streets of this city, you can pick your poison. Clouds of black and blue-white smoke billow from the exhaust pipes of buses and motorcycles. Thirteen rivers flow northwards to Jakarta Bay, each a slurry of human waste and garbage. Scavengers pick through the city's rubbish looking for recyclable plastic and cardboard. What they can't sell, they burn — batteries, rubber shoes and all. Rising smoke from burning garbage wafts between the city's skyscrapers.

Pollution in Indonesia's capital, Jakarta, is easy to see, and the causes are not hard to pinpoint. But the effects on its inhabitants' wellbeing are harder to quantify. Official data are scant, studies of environmental health are few, and those worst affected — the urban poor — are the least likely to be included in city records. Environmental scientists say that much could be done to improve living conditions for those most at risk from pollution. But without a stronger emphasis on research into urban public health, and the political will to act on its findings, experts are pessimistic about making rapid progress. "In the near future, there will be more environmental problems," says James Woodcock, a wastewater consultant to the World Bank who has lived in Jakarta for more than two decades.

With a population of about 12 million — rising to 21 million if you include the wider conurbation of surrounding towns — Jakarta is already one of the world's largest urban areas. The population of this 'megacity' is predicted to grow by a third in the next decade, part of a global trend towards urbanization. By 2007, the balance of the world's population will tip to give a majority residing in towns and cities[1]. Most of the fastest-growing cities are in developing countries (see Chart, opposite). So Jakarta may provide a pointer to a future in which urban pollution becomes a main player in the disease burden of the developing world. "The urban physical environment is going to represent a major health threat," says David Vlahov, an epidemiologist at Columbia University in New York, and president of the International Society for Urban Health.

Gridlock

In Jakarta, air quality is already at crisis point. To get an overview, I meet Budi Haryanto in his wife's office building on a Friday evening in late July. Haryanto, a professor of public health at the University of Indonesia, is waiting for the worst of the traffic to subside before driving home to a Jakarta suburb, a journey of 23 kilometres that can take almost two hours. Some two million people commute into the city each day. From a ninth floor window, Haryanto and I look down on a highway on which stalled head- and tail-lights extend as far as we can see in either direction.

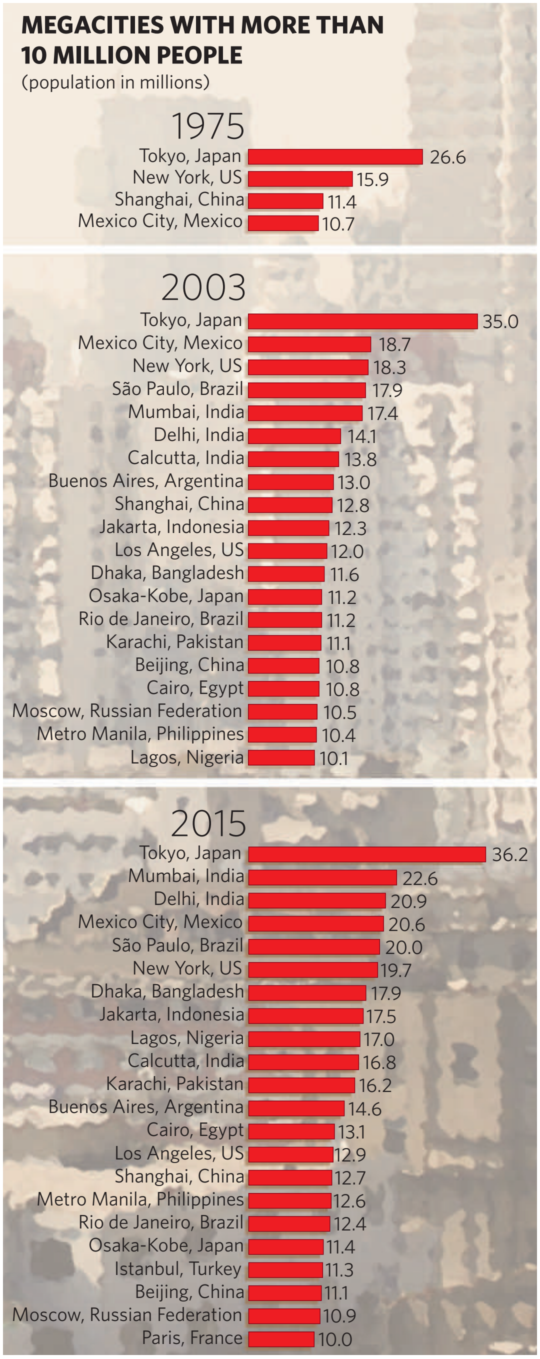
"Jakarta is getting worse," says Haryanto. Traffic is responsible for more than 70% of the nitrogen oxides and particulate matter emitted into the city's air[2]. Haryanto is frustrated that the government is not doing more to monitor and reduce the thick, nostril-burning smog, or to characterize its effects on health. "The Ministry of Health doesn't care," he laments, noting that it is dissolving its subdirectorate dealing with air pollution.

The limited available data paint an ugly picture. Respiratory inflammation accounts for 12.6% of deaths in Jakarta, twice the proportion in the rest of the country[3]. And estimates based on reported pollution levels attribute more than a million asthma attacks and several thousand premature deaths per year in the city to airborne soot and other particles[2].

Aside from the sheer volume of traffic, the main problems are poor fuel quality, and a failure to equip vehicles with emissions-control technologies such as catalytic converters. There have been some small steps forward:

before 2001, many vehicles in Jakarta used leaded fuel. At that time, about 35% of Jakartan elementary school students had levels of lead in their blood above the World Health Organization (WHO) safety guideline of 10 micrograms per decilitre[4]. This has now dropped to less than 3%, according to Haryanto's preliminary measurements. But he is concerned that the compound that replaced lead creates emissions of benzene, a known carcinogen. "I suggested to the government that they monitor benzene in the air," says Haryanto. "But they said: 'No funding'."

Although Jakarta's horrendous air quality is evident from a high-rise window, experiencing the city's problems with water pollution and solid waste requires an excursion to street level. Kampung Kandang, a north Jakartan slum, faces a river and backs on to a swamp. I stand on the riverbank, watching the eerily still water slip by. A film of grease coats the surface, broken by plastic bags and other detritus. To avoid paying for garbage collection — which is intermittent, anyway — people drop their rubbish in the river. Downstream, a barrage of trash has collected on an obstacle. The sulphurous smell is overpowering. Next to me, a man flings a wokful of oil into the water.



SOURCE: REF. 1

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Scavengers scale the massive landfill at Bantar Gebang seeking things they can recycle and sell.

Dirty old town

Kampung Kandang is typical of the illegal squatter settlements that line rivers and railway tracks throughout Jakarta, or sit tucked beneath the city's flyovers. It is a microcosm of the city's problems with water, sewage and solid waste. To the rear of the settlement, I watch a chicken in the swamp, scratching on an undulating surface of garbage, oblivious that it isn't on solid ground. The communal water tap opens into a bucket that hangs right above the swamp water that residents use as a latrine. Nearby, an elderly woman wades in the water, collecting swamp plants to sell for wicker.

The public toilet in Kampung Kandang costs up to US$0.10 to use — no small sum for a family living on about US$2.50 a day. "So people just do it everywhere," says community leader Miftahul Falah. Water pressure from the tap is low, Falah adds, so the villagers rely on water vendors, who sell 60 litres of water for about US$0.20 — several times what wealthy Jakartans pay for water from a utility company.

Even for legal residents, supplies are limited. Piped water reaches less than 60% of Jakartans, and is safe for drinking only after being boiled. About half of the supply is lost because of illegal connections and leaks. Water shortages have led many residents to tap into groundwater beneath the city. As a result, salt water is seeping into the aquifer, and subsidence has caused parts of the city to sink by a metre or so over the past decade.

Garbage-clogged waterways and the fact that about 40% of Jakarta now lies below sea level conspire to cause annual floods. These hit the poor, low-lying north of the city particularly hard, bringing a litany of health problems. "If the flood lasts a long time, maybe three days," says Falah, "people start to get sick with diarrhoea and rashes."

Less than 3% of the 1.3 million cubic metres of sewage generated each day in greater Jakarta reaches a treatment plant. More than a million septic tanks are buried beneath the city, and these have contaminated most of the city's wells with faecal coliform bacteria. What's more, truck drivers hired to pump the tanks often dump their loads, untreated, into waterways.

Solid-waste management is similarly chaotic. The city's Bantar Gebang landfill is a case in point — soil is applied only every few weeks and leachate is inadequately treated, says Widhi Handoko, an instructor in solid-waste management at the Ministry of Public Works. An army of 6,000 scavengers works the mountains of garbage. Like post-apocalyptic sherpas, clad in rubber boots and with wicker baskets strapped to their backs, they travel in the wake of bulldozers, plucking recyclables from the stinking heap.

Heaps of trouble

Although Bantar Gebang is nearing the end of its 20-year design lifetime, its representatives say that there is no option but to keep it open while the city seeks alternatives. A private company has developed land for a new waste-disposal site, but local residents have protested loudly. The municipal government recently announced it will build four incinerators. But this is an expensive option, and may cause other environmental and health hazards.

Many people in Jakarta's poor neighbourhoods say their health is fine, despite the filth that surrounds them. But experts believe that poor sanitation is a serious health issue. Ministry of Health records show gastroenteritis is by far the most frequent disease diagnosis at local clinics and hospitals. The incidence of dengue fever has also exploded in recent years. "It is not normally an urban health issue," says Jan Speets, an adviser with the WHO in Jakarta. But flooding and the piles of rubbish throughout the city have created breeding opportunities for the mosquitoes that spread the disease.

Experts in public health urge more and better research to quantify the health problems caused by poor sanitation and waste management. "There are no real studies available to reveal what's going on in the city," complains Jaap van Dissel, an infectious-disease specialist at the Leiden University Medical Center in the Netherlands. His recent investigation of the food- and water-borne diseases typhoid and paratyphoid in east Jakarta found that doctors over-diagnose the former by up to tenfold because blood cultures that confirm the infection are not normally done[5]. This illustrates the need to improve clinical diagnoses before attempting potentially expensive campaigns to address problems with public health, says van Dissel: "It's important to know your enemies before you start shooting."

Many of Jakarta's problems are shared by other megacities in the developing world. Most have large illegal shanty towns, and face similar issues with pollution and waste management. For instance, recent flooding in and around Mumbai in India, attributed in part to clogged drainage throughout the city, killed more than a thousand people, and brought water-borne diseases in its wake.

Scrubbing up

Some developing-world megacities have taken steps to clean themselves up. Mexico City's appalling smog is now beginning to clear thanks to the introduction of catalytic converters and improvements in fuel quality[6]. And the Indian capital of New Delhi is experiencing similar gains after converting its public transport to run on compressed natural gas.

So what are the chances of Jakarta following suit? Experts say that solving the city's problems with environmental health will require genuine political commitment to pay for research and monitoring to characterize the problems, and spending on the infrastructure needed to solve them. Given a legacy of official corruption, and the continuing hangover from the Asian economic crisis of 1997, the obstacles are formidable — public spending on infrastructure is running at 80% less than during the heady days of the mid-1990s, when Asia's economy was booming[7].

So far, politicians seem more interested in sweeping pollution under the carpet, rather than tackling the problems it causes head-on. After the WHO labelled Jakarta the world's third most polluted metropolis in the early 1990s, air-quality monitoring equipment was moved to residential areas with lower levels of pollution.

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Kampung Kandang's communal tap opens into a bucket by the trash-choked swamp that doubles as a toilet.

> "A film of grease coats the river's surface, broken by plastic bags and other detritus. To avoid paying for garbage collection people drop their rubbish in the river. The sulphurous smell is overpowering."

Ritola Tasmaya, secretary to the governor of Jakarta, defends the municipal government's record, pointing to developments such as a recently built busway, which will later incorporate new buses running on compressed natural gas. Tasmaya blames continuing problems with environmental health on insufficient budgets and limits to the city government's authority — rivers, he notes, remain the responsibility of the national government. "Jakarta as a capital city needs special support from the central government," Tasmaya concludes. "The infrastructure must be good enough so that people who come here for business, tourism and investment can be served."

Foreign specialists say that significant progress could be made if existing environmental regulations were properly enforced. "It's very difficult for a government that's known to be corrupt to enforce laws," says Woodcock. But the good news is that, after years of dictatorship and corruption, Indonesia is slowly becoming more democratic. Last year, the country gained its first directly elected president, Susilo Bambang Yudhoyono. And 2007 will see the first direct election for the governor of Jakarta.

For now, many of the city's residents have more immediate priorities than reducing pollution. "Income is still low," says Basah Hernowo, director of settlements and housing at the National Development Planning Agency, an arm of the central government. "People do not care about environmental quality. They are still thinking about their stomachs." But problems such as flooding and waste mismanagement are getting so bad that people are beginning to call for change. As democracy takes root, environmental health may slowly move up the list of political priorities. "In the end," Woodcock says, "I feel optimistic that there will be progress." ■

Jessica Marshall is a science writer currently travelling in Asia.

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