

# Sustainable design of sanitation system based on material and value flow analysis for urban slum in Indonesia

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## 6 Sustainable design of sanitation system based on material and 7 value flow analysis for urban slum in Indonesia

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17

18 **Abstract** Material flow analysis (MFA) and value flow analysis (VFA) were applied to the sanitation  
19 system in an urban slum in Indonesia. Based on the results of the MFA and VFA, garbage and excreta  
20 disposal costs were evaluated to be 0.7% and 1.1%, respectively, of per capita income. Such value flows  
21 seem reasonable in light of the recognized affordability to pay (ATP) standard. However, current excreta  
22 disposal methods create negative impacts on downstream populations. Because such disadvantages do not  
23 go back to disposers, but passed to downstream, the current value flow structure does not motivate  
24 individual toilet users to install treatment facility. . Based on current material and value flow structures, a  
25 resource recycling sanitation system scenario was examined. Based on VFA, an affordable initial cost for  
26 such a system was calculated; this was found to be comparable in price to a cheaper composting toilet that  
27 is currently available in the market.

28

29 **Keywords** material flow, value flow, resource recycling system, sustainable design, initial cost, urban  
30 slum

31

32

## 33 1 Introduction

34

35 Highly populated urban areas require large material inflows of food for people. Although this incoming  
36 materials is consumed, it does not disappears, because waste materials is generated, which needs to be

1 disposed of in some manner, mainly as solid waste and as waste water, including toilet waste water. If the  
2 urban system does not introduce systems to manage these material outflows, unfavorable wastes  
3 accumulate in the urban area or flow to unfavorable locations, such as into surface and ground water  
4 reservoirs, both of which are usually important water sources. Such problems can be observed in many  
5 developing countries [1–3], and although it is recognized that solutions to such problems are needed,  
6 investment in outflow systems tends to be given lower priority because they do not have clear direct  
7 benefits, unlike projects such as production, supply, and transportation.

8 On the other hand, sustainability has recently been recognized as important factor for societies system.  
9 Several types of resource recycling toilets and wastewater treatment systems for reuse have been proposed  
10 as sustainable sanitation system technologies [4–6]. Although these technologies have the advantage, that  
11 they can create value from unwanted waste, they need to be embedded in system designed suitably to  
12 manage equipment outflow. It is therefore important to understand current and future material flows in and  
13 around targeted urban areas. Material flow analysis (MFA) or substance flow analysis (SFA) are suitable  
14 methodologies for this purpose. The application of the MFA to sanitation systems has been attempted in  
15 several studies, some of which considered sanitation systems as a part of material flows [7,8], and some of  
16 which focused mainly on sanitation system [9,10]. However these studies describe current material flows  
17 and only providing the conceptual description of possible improvements.

18 In an actual application, the optimization of the material flow design is not sufficient to drive the system.  
19 Successful material flow programs needs to be designed such that they benefit all stakeholders and  
20 incorporate well planned value chains. Therefore, it is believed that both material flow and value flow  
21 should be considered simultaneously. In this study, material flow is attempted to be related with value flow  
22 for designing sustainable sanitation systems for a slum area in Bandung, Indonesia, which have been  
23 studied comprehensively.

## 26 2 Materials and methods

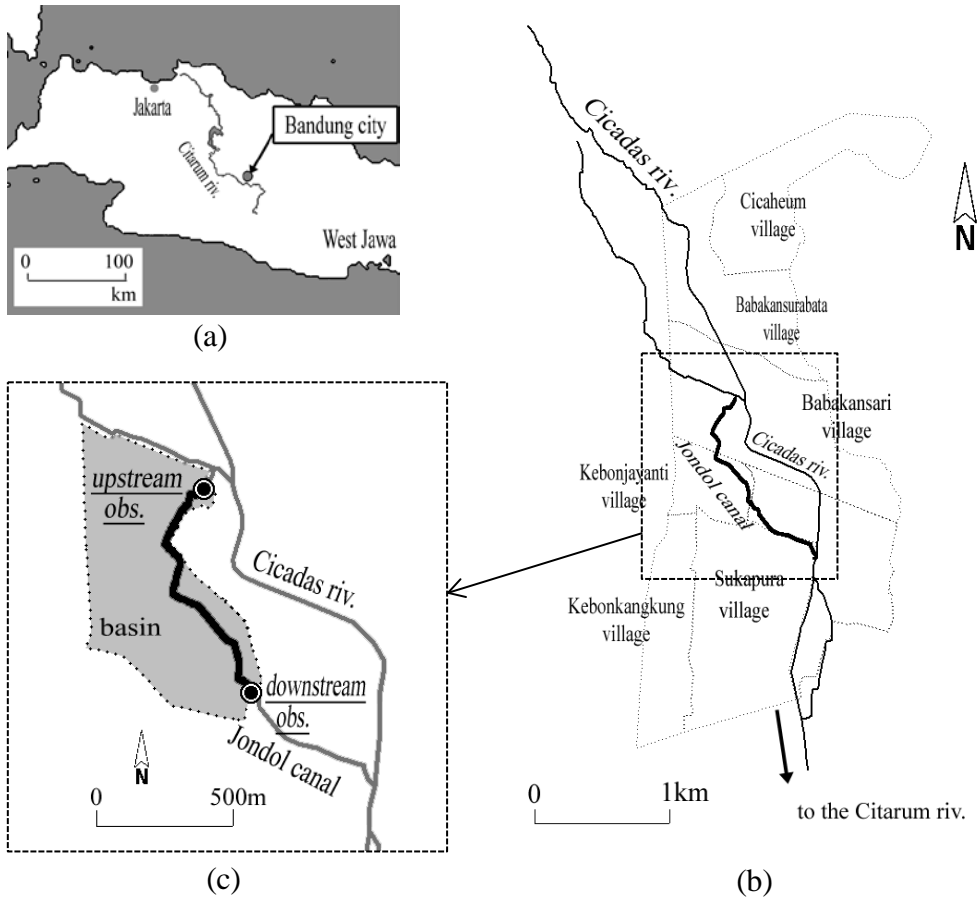
### 28 2.1 Overview of study site

29  
30 Bandung is the fourth largest city in Indonesia, with a population of 2.5 million [11]. It is in the inland part  
31 of west Java and is located upstream of the Citarum River, a major source of water for the capital, Jakarta  
32 (Fig. 1(a)). Only 16% of the domestic wastewater generated in Bandung City is treated, as the city has only  
33 one treatment plant, located in the suburbs [12]. The Kiaracandong sub-district is located near the center of  
34 Bandung city, and is known as the city's largest slum. According to 2006 local statistics, Kiaracandong has  
35 a population of 116000 living within an area of 6.1 km<sup>2</sup>.

36 Two types of field surveys were conducted. One was conducted in the Jondol Canal [13], which flows  
37 through central Kiaracandong into the Cicadas River, which is a tributary of the Citarum River. In the area  
38 surveyed, there were no houses connected to the sewerage system feeding the treatment plant. Figure 1(c)

1 shows the measurement locations and catchment of the studied section of the Jondol Canal, with a distance  
2 of 960 m between the two observation sites. This area of the catchment was measured to be 0.41 km<sup>2</sup> and,  
3 as determined by previous investigations and local statistics, has a population of 16240 people and 3585  
4 households. The other survey was conducted in the Jondol Canal catchment area. In this survey, sixty-two  
5 families living near the canal were interviewed about their water use, their wastewater disposal, and other  
6 related matters [13].

7



8

9 **Fig. 1** Location of studied area: (a) location of Bandung City; (b) Kiaracandong Sub District; (c) observatories and  
10 catchment

11

## 12 2.2 Data sources

13

14 The results of field surveys on river water [13], domestic wastewater [13,14], and garbage disposal and  
15 collection [15], in addition to official statistics for Indonesia [16], were used as the main data.

16

## 1 2.3 Methods

2

3 MFA and SFA were used to analyze current and future sanitation systems from a comprehensive and  
 4 practical viewpoint. The subjects covered in the MFA included excrement as well as all related materials,  
 5 namely, water and food. The SFA was conducted along a similar framework, focusing on nitrogen and  
 6 phosphorus which, as major components of fertilizers, are important factors in resource recycling systems.  
 7 When data for the slum area were unavailable, data from statistics and literature on Indonesia or other  
 8 South-east Asian countries were used for extrapolation. The project boundary was set as the catchment  
 9 area described in Fig. 1(c). All the data were expressed in terms of per capita years, because both material  
 10 and value flows are discussed together in this study and the use of such unit is meaningful to the study of  
 11 value flow.

12 MFA and SFA were also used for estimating value flow. In contrast to material and substance flows,  
 13 value flow can be measured in a number of ways. Some can be definitely measured in quantitative factors  
 14 such as prices or monetary value, whereas some can be only evaluated in qualitative factors, such as status  
 15 or comfort derived. In this study, the quantitative values were evaluated based on the available data,  
 16 whereas qualitative values were simply determined to be positive or negative by assessing the directions of  
 17 material and value flows.

18 Material, substance, and value flow analysis were conducted for two scenarios: one representing current  
 19 conditions, and the other assuming the implementation of a resource recycling sanitation system involving  
 20 the installation of a urine diversion aerobic composting toilet [17] in each household. The framework  
 21 proposed and discussed quantitatively by Ushijima [14] for the collection of urine and compost for  
 22 integration with existing garbage collection systems, wherein organic solid waste is processed in a  
 23 composting toilet along with feces, was applied.

24 Successful diffusion of this resource recycling system primarily depends on each household's decision  
 25 of whether to install the composting toilet. This decision is based on the following criterion:

$$26 \quad (\text{Initial cost} / \text{expected lifetime}) < (\text{WTP for excreta disposal}) + (\text{income from selling excreta}), \quad (1)$$

27 where WTP is "willingness to pay". Here, *WTP for excreta disposal* is estimated by

$$28 \quad (\text{WTP for excreta disposal}) = (\text{Current excreta disposal cost}) + (\text{Initial cost for water flush toilet} / \text{expected} \\ 29 \quad \quad \quad \text{lifetime}), \quad (2)$$

30 where the *Current excreta disposal cost* is equal to the sum  $O_c11+O_c12$ , given in Table 1

31

32 **Table 1** Mass, Phosphorus, Nitrogen and value of each arrow in current material flow

| ID               | supplied item | mass<br>/(kg·(year·capita) <sup>-1</sup> ) | P | N | value<br>/(Rp·(year·capita) <sup>-1</sup> )<br>/(% against income) | data source   |
|------------------|---------------|--|---|---|--|---|
| I <sub>c</sub> 1 | water         | 32000                                      | 0 | 0 | + 110000<br>(2.8%)   | mass, value: average of 3<br>households in Ushijima [14]. P, N:<br>regarded as ignoreable |

|                  |               |           |     |     |                      |   |
|------------------|---------------|-----------|-----|-----|----------------------|---|
| I <sub>c2</sub>  | food          | 170       | 1.3 | 6.0 | + 1400000<br>(35.9%) | mass, value: Gunawan[16], P, N:<br>blackwater + solid waste   |
| I <sub>c3</sub>  | electricity   | 0         | 0   | 0   | + 170000<br>(4.4%)   | value: average of 3 households in<br>Ushijima[14],<br>mass, P, N: meaningless   |
| O <sub>c1</sub>  | blackwater    | 14000     | 1.2 | 5.9 | ± 0<br>(0%)          | mass: I <sub>c1</sub> ×0.41[14] + O <sub>c11</sub> + O <sub>c12</sub> ,<br>P, N: O <sub>c11</sub> + O <sub>c12</sub><br>mass, P, N: Ushijima[14],   |
| O <sub>c11</sub> | feces         | 33        | 0.3 | 0.9 | -13000<br>(0.3%)     | value: water consumption for<br>defecation (water cost × percentage<br>of water use for defecation)<br>mass, P, N: Ushijima[14],  |
| O <sub>c12</sub> | urine         | 370       | 0.9 | 5.0 | -32000<br>(0.8%)     | value: water consumption for<br>urination (water cost × percentage<br>of water use for urination)<br>mass: I <sub>c1</sub> -O <sub>c1</sub> ,<br>P, N: total wastewater (maximum in<br>Ushijima [14]) - O <sub>c1</sub><br>mass: Ushijima [14], |
| O <sub>c2</sub>  | graywater     | 19000     | 1.0 | 0.0 | ± 0<br>(0%)          | P, N: total wastewater (maximum in<br>Ushijima [14]) - O <sub>c1</sub><br>mass: Ushijima [14],  |
| O <sub>c3</sub>  | solid waste   | 67        | 0.1 | 0.2 | -28000<br>(0.7%)     | P, N (unit): Aramaki & Thuy [8],<br>value: collection fee (Ushijima<br>[14])  |
| O <sub>c31</sub> | junk material | (no data) | 0   | 0   | +                    | P, N: non-organic is regarded as 0  |
| O <sub>c32</sub> | solid waste   | (no data) | 0.1 | 0.2 | -                    | D3-D31  |
| O <sub>c33</sub> | junk material | (no data) | 0   | 0   | +                    | P, N: non-organic is regarded as 0  |
| O <sub>c34</sub> | accumulation  | (no data) | 0.1 | 0.2 | -                    | D32-D33<br>mass, P, N: meaningless  |
| O <sub>c4</sub>  | work force    | 0         | 0   | 0   | + 3900000<br>(100%)  | value: average of 3 households in<br>Ushijima[14]<br>Ushijima[14],  |
| R <sub>c1</sub>  | river inflow  | 52000     | 0.4 | 1.3 | ± 0<br>(0%)          | N: NH <sub>4</sub> -N + NO <sub>2</sub> -N + NO <sub>3</sub> -N<br>P: PO <sub>4</sub> -P<br>Ushijima[14],   |
| R <sub>c2</sub>  | river outflow | 110000    | 1.2 | 3.5 | ± 0<br>(0%)          | N: NH <sub>4</sub> -N + NO <sub>2</sub> -N + NO <sub>3</sub> -N<br>P: PO <sub>4</sub> -P<br>Ushijima[14]  |
| R <sub>c3</sub>  | mosque        | 8300      | 0   | 0   | ± 0<br>(0%)          | Ushijima[14]  |

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## 3 3 Results

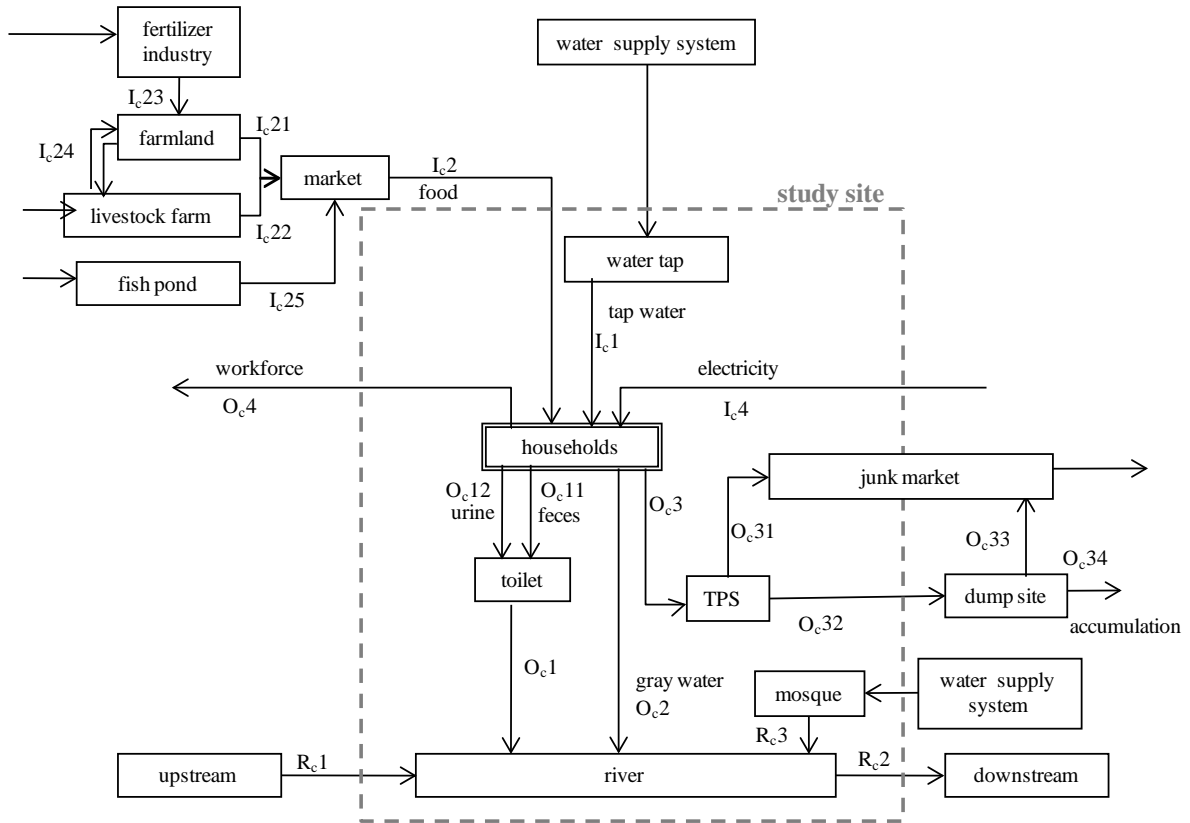
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1 3.1 Current material flow

2

3 **Figure 2** shows current material flows. Total mass flow, phosphorus mass flow, nitrogen mass flow, and  
 4 total value flows are summarized in **Table 1**. Note that several value flows, namely,  $I_{c21}$ ,  $I_{c22}$ ,  $I_{c23}$ ,  $I_{c24}$   
 5 and  $I_{c25}$  were not quantified in this study.

6



7

8 **Fig. 2** Current material flow

9

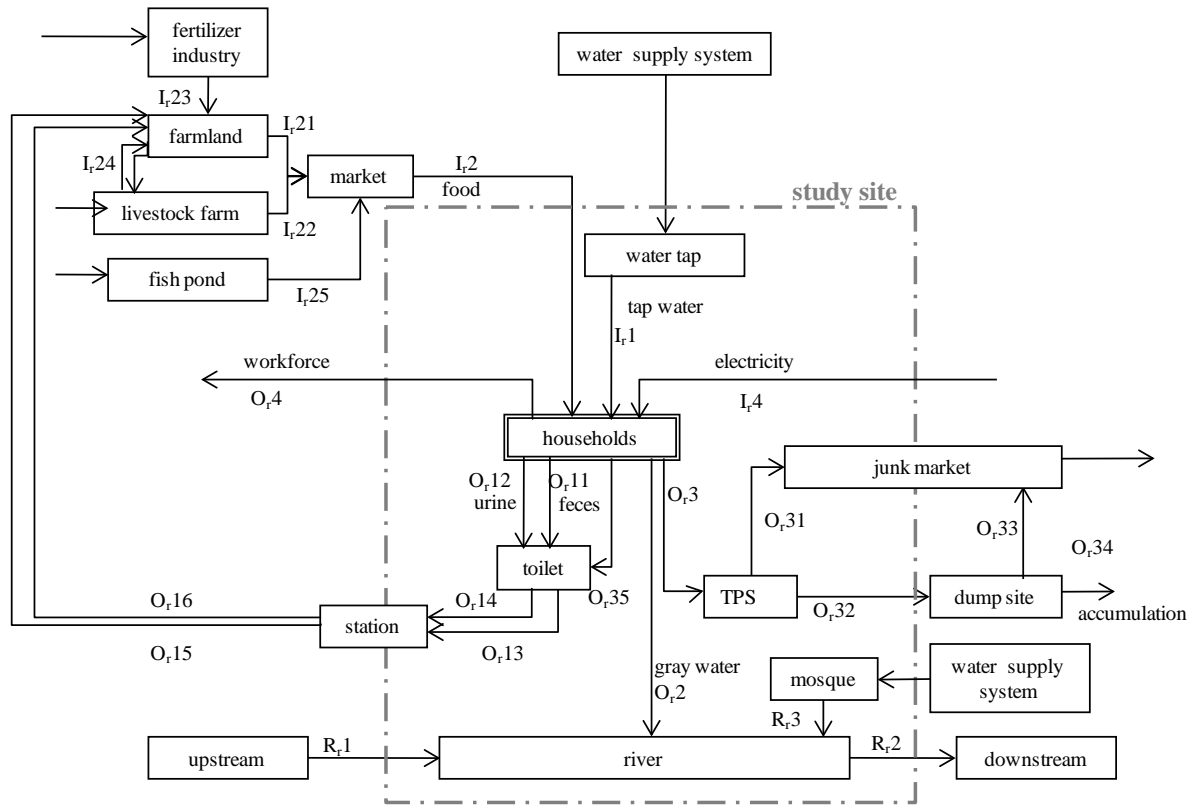
10 3.2 Material flow of resource recycling sanitation system

11

12 **Figure 3** shows material flows under a future scenario in which a resource recycling sanitation system is  
 13 applied. Total mass flow, phosphorus mass flow, nitrogen mass flow, and total value flows are summarized  
 14 in **Table 2**. Note that several mass flows, namely,  $I_r21$ ,  $I_r22$ ,  $I_r23$ ,  $I_r24$ , and  $I_r25$  were not quantified in this  
 15 study.

16

1



2

3 **Fig. 3** Material flow of resource recycling scenario

4

5 **Table 2** Mass, phosphorus, nitrogen and value of each arrow in material flow of resource recycling sanitation system.

| ID                | supplied item   | mass/<br>(kg·(year·capita) <sup>-1</sup> ) | P/<br>(kg·(year·capita) <sup>-1</sup> ) | N/<br>(kg·(year·capita) <sup>-1</sup> ) | value/<br>(Rp·(year·capita) <sup>-1</sup> )<br>(% against income) | data source   |
|-------------------|-----------------|--|---|---|---|---|
| I <sub>r</sub> 1  | water           | 32000                                      | 0                                       | 0                                       | + 110000<br>(2.8%)  | mass, value: average of 3 households in Ushijima[14].<br>P, N: regarded as ignorable                                    |
| I <sub>r</sub> 2  | food            | 170  | 1.3                                     | 6.0                                     | + 1400000<br>(35.9%)  | mass, value: Gunawan[16], P, N: blackwater + solid waste  |
| I <sub>r</sub> 3  | electricity     | 0  | 0                                       | 0                                       | + 170000<br>(4.4%)  | value: average of 3 households in Ushijima[14], mass, P, N: meaningless   |
| O <sub>r</sub> 11 | feces           | 33   | 0.3                                     | 0.9                                     | variable  | mass, P, N: Ushijima[14], value: water consumption for defecation (water cost × percentage of water use for defecation) |
| O <sub>r</sub> 12 | urine           | 370  | 0.9                                     | 5.0                                     | variable  | mass, P, N: Ushijima[14], value: water consumption for urination (water cost × percentage of water use for urination)   |
| O <sub>r</sub> 13 | processed feces | variable                                   | 0.3                                     | < 0.9                                   | variable  | P, N: = O <sub>r</sub> 11   |



|                   |                 |           |     |       |                     |  |
|-------------------|-----------------|-----------|-----|-------|---------------------|--|
| O <sub>r</sub> 14 | processed urine | variable  | 0.9 | < 5.0 | variable            | P, N: = O <sub>r</sub> 12  |
| O <sub>r</sub> 15 | collected feces | variable  | 0.3 | < 0.9 | variable            | P, N: = O <sub>r</sub> 11  |
| O <sub>r</sub> 16 | collected urine | variable  | 0.9 | < 0.9 | variable            | P, N: = O <sub>r</sub> 12  |
| O <sub>r</sub> 2  | graywater       | 19000     | 1.0 | 0.0   | ± 0<br>(0%)         | mass: I <sub>c</sub> 1-O <sub>c</sub> 1, P, N: total wastewater<br>(maximum in Ushijima [14]) - O <sub>c</sub> 1 |
| O <sub>r</sub> 3  | solid waste     | 17        | 0.0 | 0.0   | -28000<br>(0.7%)    | mass: Ushijima[14], P, N: non-organic<br>is regarded as 0, value: collection fee<br>(Ushijima[14])               |
| O <sub>r</sub> 31 | junk material   | (no data) | 0   | 0     | +                   | P, N: non-organic is regarded as 0   |
| O <sub>r</sub> 32 | solid waste     | (no data) | 0.0 | 0.0   | -                   | D3-D31   |
| O <sub>r</sub> 33 | junk material   | (no data) | 0   | 0     | +                   | P, N: non-organic is regarded as 0   |
| O <sub>r</sub> 34 | accumulation    | (no data) | 0.0 | 0.0   | -                   | D32-D33  |
| O <sub>r</sub> 35 | organic waste   | 50        | 0.1 | 0.1   | +                   | mass: Ushijima [14],<br>P, N (unit): Aramaki & Thuy [8]  |
| O <sub>r</sub> 4  | work force      | 0         | 0   | 0     | + 3900000<br>(100%) | mass, P, N: meaningless, value: average<br>of 3 households in Ushijima [14]                                      |
| R <sub>r</sub> 1  | river inflow    | 52000     | 0.4 | 1.3   | ± 0<br>(0%)         | Ushijima[14], N: NH <sub>4</sub> -N + NO <sub>3</sub> -N<br>P: PO <sub>4</sub> -P                                |
| R <sub>r</sub> 2  | river outflow   | 97000     | 0.8 | 3.5   | ± 0<br>(0%)         | Ushijima[14], N: NH <sub>4</sub> -N + NO <sub>3</sub> -N<br>P: PO <sub>4</sub> -P, reaching ratio of N, P: 0.36  |
| R <sub>r</sub> 3  | mosque          | 8300      | 0   | 0     | ± 0<br>(0%)         | Ushijima[14]   |

1

2

## 3 4 Discussion

4

### 5 4.1 Current material flow

6

7 Using material flow and value flow analysis, the value flow in and around an urban slum family were  
8 analyzed, not only in terms of easy-to-price factors or quantitative flows but also in terms of  
9 difficult-to-price factors or qualitative flows, such as garbage disposal and excreta disposal. Based on the  
10 result, “costs for disposal” for garbage and wastewater were determined. These values, listed in Table 1 are  
11 approximately 0.7% and 1.1% of per capita income for garbage disposal and for urine and excreta disposal,  
12 respectively. The World Bank has roughly evaluated benchmarks for affordability to pay (ATP) as 2% and  
13 1% of consumable per capita income for garbage collection service and sewerage service, respectively [18],  
14 similar to the current costs derived here. Thus, current value flows for garbage and excreta disposal seem  
15 reasonable for people in light of such benchmarks. However, the material flow of excreta into the river is  
16 clearly causing deterioration of the water environment. Because this value loss has a negligible direct

1 effect, and because the disadvantages apply to populations downstream instead of to disposers, it would  
2 seem that the structure of the current value flow would impede efforts to improve the water environment.

## 4 4.2 Resource recycling system

6 A proposed resource recycling sanitation system would not discharge excreta to the river; rather such  
7 waste would be sent to farms, where it would have positive value as a fertilizer. From the catchment area  
8 studied, the system would remove almost all the nitrogen and half of the phosphorus discharged, and  
9 therefore, the net flux of nitrogen and phosphorus through the river under a recycling scenario (see Fig.3:  
10  $R_r2-R_r1$ ) would be less than under current conditions (Fig.2:  $R_c2-R_c1$ ). The positive impacts on river water  
11 quality resulting from the introduction of resource recycling sanitation would be potentially large.

12 As it is a source of nutrients, excreta has good potential for the generation of value through use as  
13 fertilizer. However, the value of compost made from human excreta may also be discounted relative to  
14 chemical fertilizers because of psychological resistance. Further, the quality or handling of the processed  
15 excreta may also affect the value of the resulting compost. However, the price of synthetic fertilizers has  
16 been rising the last decade, and if this rise continues, the incentive of saving costs through substitution may  
17 overcome the psychological barriers.

18 In any event, the exact value of human excreta is currently difficult to evaluate. A case study of one  
19 company selling liquid fertilizer made from human urine seems suitable as a reference [19]. The company  
20 pays 1000 Rupiah·L<sup>-1</sup> to people as compensation for urine offer. Assuming that one liter of urine is  
21 produced per capita per day, this price corresponds to 365000 Rupiah·(capita·year)<sup>-1</sup>, equivalent to 9% of  
22 per capita income, which is listed in Table 1 as O<sub>c</sub>4.

23 In the area studied, the initial cost of a water flush toilet is reported to be approximately 2000000 Rupiah  
24 [14]. Assuming a family size of four people and a toilet lifetime of 15 years (which is standard in Japan),  
25 the WTP is thus estimated at 79000 Rupiah·(capita·year)<sup>-1</sup>. If we apply the excreta price mentioned above  
26 as an optimum estimation, affordable initial cost for resource recycling sanitation system is estimated as

$$(Initial\ cost / lifetime) < 4400000\ Rupiah \cdot (capita \cdot year)^{-1}, \quad (3)$$

28 For a 15-year lifetime composting toilet, the estimated affordable initial cost for a four person family  
29 would be 27000000 Rupiah, equivalent to approximately 3200 USD according to the June 2011 exchange  
30 rate. This is similar in price to a cheaper composting toilet (approximately 2000 USD) currently available  
31 in the market.

## 34 5 Conclusions

36 In this study, for an urban slum, the material and value flows of water, sanitation related materials,  
37 nitrogen, and phosphorus were calculated and plotted. The value flow analysis evaluated garbage disposal

1 cost and excreta disposal cost at 0.7% and 1.1%, respectively, of household income, which represents a  
2 reasonable cost to disposers. However, under the current disposal scheme, negative value due to excreta  
3 disposal appears to be passed on to downstream populations. The structure of this value flow suggests that  
4 little attention is paid to the negative externalities, indicating that a solution in this case may be difficult to  
5 obtain.

6 The affordable initial cost of a new resource recycling system was evaluated and compared with the  
7 costs of a currently used commercial compost toilet by evaluating equipment lifetimes and potential  
8 income streams available from the sale of human excrement fertilizers. To estimate a value for the human  
9 excrement fertilizer, real-world case study in Indonesia, in which money was paid in exchange for human  
10 urine, was referred to. The evaluated affordable initial cost derived was sufficiently comparable to the  
11 price of a cheaper composting toilet currently available in the market. This implies that such a resource  
12 recycling system is feasible even in an urban slum.

13  
14  
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