

## Community-based wastewater treatment systems and water quality of an Indonesian village

H. S. Lim, L. Y. Lee and S. E. Bramono

### ABSTRACT

This paper examines the impact of community-based water treatment systems on water quality in a peri-urban village in Yogyakarta, Indonesia. Water samples were taken from the wastewater treatment plants (WWTPs), irrigation canals, paddy fields and wells during the dry and wet seasons. The samples were tested for biological and chemical oxygen demand, nutrients (ammonia, nitrate, total nitrogen and total phosphorus) and *Escherichia coli*. Water quality in this village is affected by the presence of active septic tanks, WWTP effluent discharge, small-scale tempes industries and external sources. We found that the WWTPs remove oxygen-demanding wastes effectively but discharged nutrients, such as nitrate and ammonia, into irrigation canals. Irrigation canals had high levels of *E. coli* as well as oxygen-demanding wastes. Well samples had high *E. coli*, nitrate and total nitrogen levels. Rainfall tended to increase concentrations of biological and chemical oxygen demand and some nutrients. All our samples fell within the drinking water standards for nitrate but failed the international and Indonesian standards for *E. coli*. Water quality in this village can be improved by improving the WWTP treatment of nutrients, encouraging more villagers to be connected to WWTPs and controlling hotspot contamination areas in the village.

**Key words** | community-based wastewater treatment, water quality

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### INTRODUCTION

The Millennium Development Goals from the 2000 UN General Assembly Millennium Meeting aim to halve the proportion of people without sustainable access to sanitation and safe drinking water by 2015 (Cornel *et al.* 2011). About 40% of the world's population, mostly in developing countries, still lack basic sanitation and suffer the consequences of water pollution on human health (Massoud *et al.* 2009; Cornel *et al.* 2011). In cases where government efforts to provide sanitation have failed or are lacking, community-based projects have emerged, aided by non-governmental organisations (NGOs) or the private sector, to address these sanitation and water quality/human health issues (Sansom 2011).

Indonesia has one of the lowest rates of sewerage coverage in Asia, partly a result of government policy, which assigns responsibility for sanitation to households (Foley *et al.* 2001). Untreated or partially treated sewage, mostly from septic

tanks, is discharged into surface waters (rivers and drains) or allowed to seep into the ground with minimal treatment. High levels of oxygen-demanding substances, nutrients and faecal indicator organisms in septic tank effluent pollute groundwater and surface waters. This results in widespread health problems related to malaria, cholera and other causes of diarrhoea because groundwater is the main source of drinking water (Roma & Jeffrey 2010). In response to this, the Indonesian government started developing community-based wastewater treatment projects in the 1990s, funded by the government itself and external agencies such as the United Nations Children's Foundation, the Asian Development Bank, the World Bank, the Australian Government Overseas Aid Program and the Cooperative for American Remittances to Europe (CARE). Community participation was encouraged in all phases of these projects: design, construction, operation and maintenance. At the same time,

villagers who were not included in these schemes started petitioning their local governments for assistance in setting up their own municipal wastewater treatment systems (Mukherjee & Josodipoero 2000; Foley *et al.* 2001; Lasut *et al.* 2008).

This paper presents a case study of a typical Indonesian village, Sukunan Village, where village activism led to the construction and maintenance of wastewater treatment systems in their village. The villagers were increasingly concerned about the health effects of water pollution arising from inadequate wastewater treatment and farming activities associated with cattle and fertiliser usage. The villagers petitioned the government for assistance in the construction of municipal wastewater treatment plants (WWTPs). Five such systems were built in the village in 2008 and have been in operation since then.

Community-based efforts similar to those in Sukunan Village are found throughout Indonesia. There are quite a number of reports detailing these initiatives and how they have led to the success or failure of the projects (Mukherjee & Josodipoero 2000; Foley *et al.* 2001; Roma & Jeffrey 2010). However, the literature about the performance and impact of community-based sanitation systems on environmental quality is scarce and often only reports treatment efficiencies for solids and oxygen-demanding wastes (e.g. Foley *et al.*

2001). This study hopes to contribute to the growing academic literature on community-based sanitation efforts by focusing on the water quality aspects of such systems (treatment efficiencies and effluent quality) in relation to their environmental water quality using a typical Indonesian village, which has a community-based sanitation system, as a case study. We examined the extent of water pollution in the village and identified the source/s of pollution to see if the presence of the WWTPs has a positive impact on environmental quality. The water quality parameters chosen for study have an impact on human health (nutrients and *Escherichia coli*). Finally, we hope to suggest some practical measures that can improve water quality in this village as well as other Indonesian villages.

## STUDY SITE

Sukunan Village (area 0.2 km<sup>2</sup>) is a small village located in the eastern part of Yogyakarta in the peri-urban part of the Special District of Yogyakarta, Java, Indonesia (Figure 1). The village population is approximately 900.

The climate of this region is humid equatorial but approaching monsoonal equatorial conditions according to



**Figure 1** | Map of Sukunan Village showing the locations of the WWTPs and the surface and subsurface sampling points.

the Köppen-Geiger climate classification system (Kottek *et al.* 2006). Annual rainfall is 1,900–2,000 mm (Smith *et al.* 1999). The dry season lasts from April/May to September. The rainy season is from October to March/April.

Details about the hydrogeological conditions of this village are based on Smith *et al.* (1999) who studied a village 3 km south of our study site. The topography of the village is flat and the area is underlain by porous, sandy volcanic deposits. The groundwater system is part of the Merapi aquifer, one of the most productive aquifers in Central Java. The aquifer is approximately 150 m thick with a shallow and a deep layer. At Sukunan, depth of the water table is about 10 to 11 m, which probably coincides with the shallow layer of the Merapi aquifer.

Land use consists of unpaved roads, gardens and trees; domestic animals (e.g. ducks, chickens and cattle) are free to roam about the village. Paddy farming is the main economic activity. Paddy fields are supplied with water from a nearby river through a network of irrigation canals running within and around the village (Figure 1). Both commercial and home-made fertilisers are used. Commercial fertilisers include urea while home-made fertilisers are made from combining vegetable waste, cow faeces and sludge from the municipal WWTPs. There are three to four small home-based industries in the village that produce compost bins and tempe, a soybean staple of the Indonesian diet. Tempe is produced by fermentation of soybeans. The soybeans are soaked, dehulled, boiled and inoculated with the fungus *Rhizopus* spp.; mycelial growth knits the soybeans into a cake that has a meaty texture (Bisping *et al.* 1993). Nout & Rombouts (1990) provide a detailed review of the tempe production process.

Cattle (about 48 cows) are kept at one location in the southeast corner of the village to minimise their movement and to centralise the collection of their faeces for composting (Figure 1).

Septic tanks were previously the main wastewater treatment system in the village. Five municipal wastewater treatment systems were installed in the village in 2008 with the help of an Indonesian NGO (Yayasan Dian Desa; <http://diandes.org/Home.html>), local government and external sources of funding. They serve about half of the village households (approximately 150 households, i.e. 30 households/system). The remaining villagers continued to

use septic tanks because they could not afford the cost of pipeline connection to the WWTPs. The municipal WWTPs include four units using the contact aeration (CA) process and one unit using the rotating biological contactor (RBC) process (Figure 1). The CA process provides biological contact filters for the microorganisms to break down wastewater through aerobic degradation; it uses a surface aerator to introduce air as an oxidant to break down municipal wastewater. The RBC process uses a series of parallel discs mounted on a rotating shaft; microorganisms attached to the disc surface provide sequential aerobic and anaerobic degradation of the wastewater as the disc is exposed to the air and subsequently submerged in wastewater (Metcalf & Eddy 2002). These WWTPs are maintained by a villager who regularly carries out checks and simple maintenance tasks such as cleaning and de-sludging. The effluent from all WWTPs is discharged into the irrigation canals which feed the paddy fields.

Drinking water for the villagers comes from wells that may be located in the house or outside. All wells in this village are at least 10 m from a septic tank in accordance with Indonesian law (Pokja AMPL 2011). Water is disinfected by boiling but a few wealthier villagers disinfect their well water by chlorination (Smith *et al.* 1999).

## METHODS

To characterise water quality within the village, water samples were taken from surface and subsurface locations throughout the village. Sampling sites include irrigation canals (11 sites), wells (13 sites), paddy fields (two sites) and wastewater effluent points (two sites). Some irrigation sampling points are directly downstream of WWTP effluent points (three sites) while others are unaffected by WWTP discharge (eight sites) (Figure 1). Water samples were collected in August and December 2011 during the dry and wet seasons, respectively.

The treatment performance of the WWTPs was examined by taking water samples from different points within the treatment process including the influent point, inside the wastewater treatment chamber, and the effluent point. This was done only for the RBC system (Site 1) and one of the CA systems (Site 3) for the following reasons. First, the effluent discharge point from the CA process at Site 2 was

inside the irrigation canal so it was not possible to get a true effluent sample. Second, the CA process at Sites 4 and 5 was not functioning in August so it was not possible to compare treatment performance for the two sampling periods.

The water quality parameters examined were chosen to reflect the oxygen demand in, and the nutrient and bacteria content of, the water. Elevated nutrient content may result in eutrophication with undesirable algal growth and subsequent smell. Elevated nitrate concentrations may cause human health problems such as methaemoglobinaemia in babies (blue-baby syndrome), and bacteria such as *E. coli* cause urinary tract infections and gastroenteric diseases.

Turbidity and pH were measured *in situ* using portable equipment. Water samples were collected by hand in clean polyethylene bottles and kept in a cooler box before being sent for analysis by an accredited Indonesian laboratory. Samples were tested for total suspended solids (TSS), biological oxygen demand (BOD<sub>5</sub>), chemical oxygen demand (COD), ammonia (NH<sub>3</sub>-N), nitrate (NO<sub>3</sub>-N), total nitrogen (TN) and total phosphorus (TP) (Table 1). Unfortunately, orthophosphate could not be tested due to equipment problems at the Indonesian laboratory. Samples for *E. coli* were obtained by professional staff from another accredited Indonesian laboratory and analysed on the same day.

## RESULTS

### Treatment performance of the Sukunan WWTPs

The RBC treatment process (Site 1, Figure 1) was able to remove TSS, BOD<sub>5</sub> and COD from sewage quite effectively. Removal efficiencies were above 75% for these water quality parameters (except BOD<sub>5</sub> in December) and were quite consistent for the two sampling occasions (Table 1). The treatment performance for nutrients was lower and more variable between the two sampling periods. For instance, the removal efficiency of nitrate varied quite considerably between August (64.9%) and December (26.6%) (Table 1). Further, the RBC system failed to remove ammonia and TN for both sampling periods (i.e. negative treatment efficiencies). The system managed to remove TP but treatment efficiency was very low, at less than 10% efficiency for both sampling periods.

The CA wastewater treatment process (Site 3, Figure 1) also removed TSS, BOD<sub>5</sub> and COD most effectively. Removal efficiencies were often above 85% (Table 1). The CA process managed to remove TP quite effectively (greater than 60% removal efficiency for both sampling periods) but failed to remove nitrate and ammonia from raw sewage (Table 1). This treatment process managed to remove some TN from raw sewage but removal efficiencies were low (30.5 and 10.7% for August and December) (Table 1). The nutrient removal efficiencies were also inconsistent between the two sampling periods. For example, samples taken during August had no ammonia removal whereas the removal efficiency for December was very high (89.6%) (Table 1).

### Comparing effluent quality with water sampled from the village

A comparison between the quality of WWTP effluent and water samples taken from different sources in the village shows the degree of water pollution within the village (Figure 2, Table 2). World Health Organization (WHO) and United States Environmental Protection Agency (USEPA) drinking water guidelines are also included in Table 2 as a reference. These drinking water guidelines cover only a limited number of water quality parameters, namely pH, NO<sub>3</sub>-N and *E. coli*.

### *E. coli*

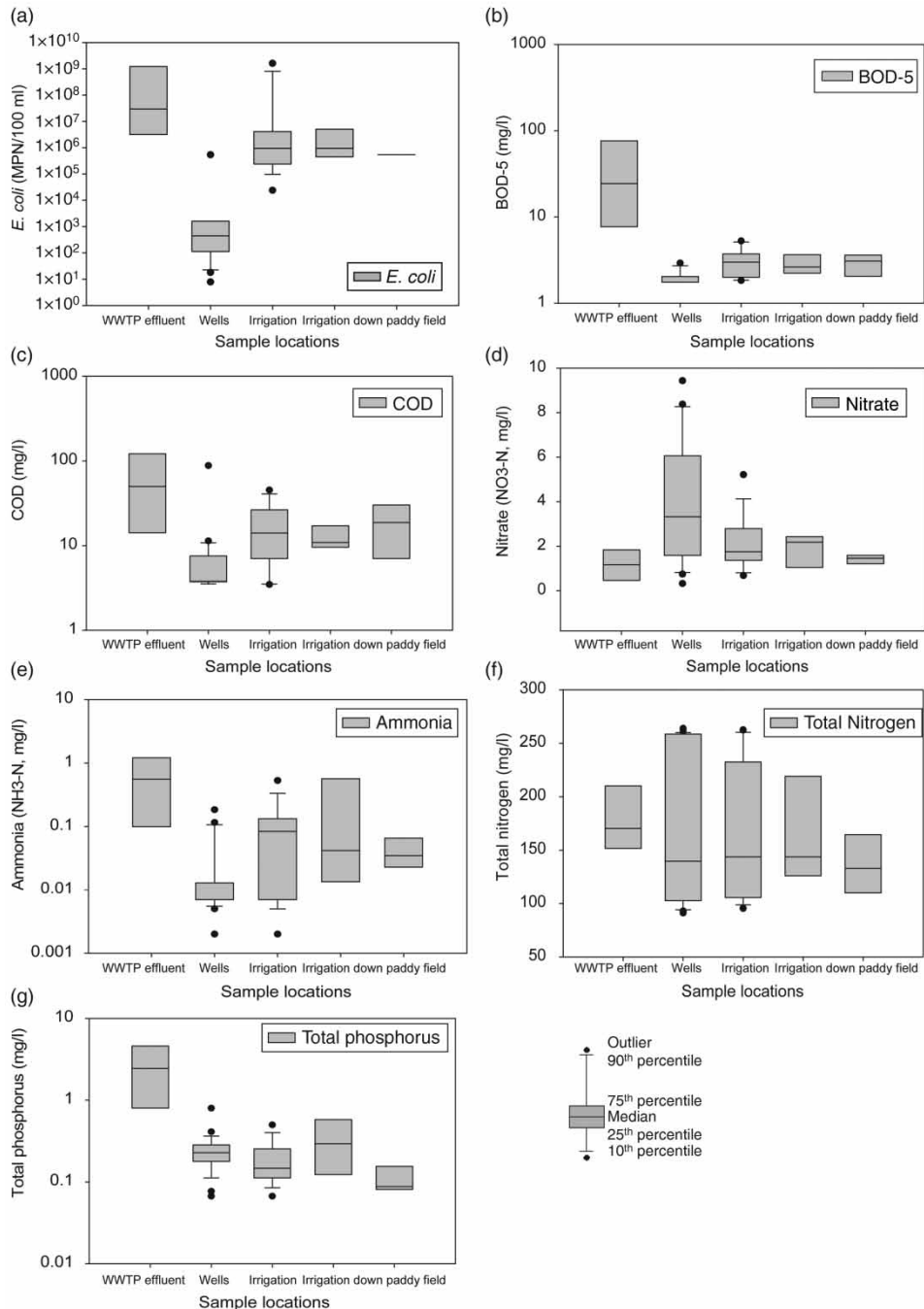
*E. coli* was present in all samples taken from the Sukunan village (Figure 2(a), Table 2). There was no clear distinction between the median *E. coli* counts found in samples from irrigation canals directly downstream of WWTP effluent discharge points and unaffected irrigation sites. Overall, the highest *E. coli* count ( $2.4 \times 10^{10}$  counts/MPN (most probable number), Figure 2(a)) was for a sample taken at a canal just upstream of the CA system (Site 2, Figure 1) and was a bit unusual as higher concentrations are expected downstream of a WWTP effluent discharge point (Figure 1). This sample might have been contaminated by village animals or localised sources from homes nearby and warrants further investigation.

*E. coli* was also detected in all well samples and varied quite significantly across the village (up to five orders of magnitude, Figure 2(a), Table 2). Some wells had counts

**Table 1** | Water quality of wastewater at different points of treatment and final effluent for two wastewater treatment plants (WWTPs), Sukunan Village

	TSS (mg L <sup>-1</sup> )		BOD <sub>5</sub> (mg L <sup>-1</sup> )		COD (mg L <sup>-1</sup> )		Nitrate (NO <sub>3</sub> -N) (mg L <sup>-1</sup> )		Ammonia (NH <sub>3</sub> -N) (mg L <sup>-1</sup> )		TN (mg L <sup>-1</sup> )		TP (mg L <sup>-1</sup> )		E. coli (MPN/100 ml)	
	Aug	Dec	Aug	Dec	Aug	Dec	Aug	Dec	Aug	Dec	Aug	Dec	Aug	Dec	Aug	Dec
<b>RBC process (Site 1)</b>																
Inlet	125.0	242.0	146.0	246.5	447.0	561.6	2.9	0.4	0.8	0.3	168.0	137.9	5.2	4.2	–	–
Inside	47.0	41.0	50.0	84.5	102.1	123.6	1.1	0.4	1.0	0.4	211.0	192.7	5.3	5.0	–	–
Effluent	8.0	37.0	40.5	88.0	84.5	133.7	1.0	0.3	0.8	0.3	173.4	167.3	4.8	3.8	5.4 × 10 <sup>6</sup>	1.6 × 10 <sup>9</sup>
Removal (%)	93.6	84.7	72.3	64.3	81.1	76.2	64.9	26.6	–2.7	–5.7	–3.2	–21.3	7.8	10.6	–	–
<b>CA process (Site 3)</b>																
Influent	102.0	528.0	110.0	187.0	215.3	294.5	0.8	0.7	0.5	0.3	211.0	249.1	5.3	2.1	–	–
Aeration tank	811.0	32.0	39.0	54.5	83.3	102.0	0.6	0.3	1.2	0.0	211.0	310.7	5.3	2.1	–	–
Effluent (next to biogas)	12.5	18.0	7.5	8.2	13.9	15.1	1.3	2.2	1.4	0.0	146.5	222.4	0.9	0.8	2.4 × 10 <sup>6</sup>	5.4 × 10 <sup>7</sup>
Down stream of biogas site	10.0	20.0	3.6	2.9	10.4	18.9	2.3	2.4	1.4	0.0	127.7	195.7	0.3	0.7	1.4 × 10 <sup>6</sup>	5.4 × 10 <sup>5</sup>
Removal (%)	87.7	96.6	93.2	95.6	93.5	94.9	–60.0	–194.8	–170.9	89.6	30.5	10.7	83.2	63.6	–	–
Removal efficiency of other Indonesian WWTP <sup>a</sup>	67	55	47	–	–	–	–	–	–	–	–	–	–	–	–	–
Method of analysis	APHA 2540-D, 2005		APHA 5210-B, 2005		APHA 5220-C, 2005		SNI 06.2480, 1991		IKM/5.4.38/B LK-Y		APHA4500-N.Org C		IKM/5.4.40/BLK-Y		APHA 2005, Section 9221-E	

<sup>a</sup>Based on eight community-based WWTPs in Indonesia (Foley et al. 2001).



**Figure 2** | Boxplots of (a) *E. coli*, (b) BOD<sub>5</sub>, (c) COD, (d) nitrate, (e) ammonia, (f) TN, (g) TP for both sampling trips sampled from WWTP effluent, groundwater samples (Wells), irrigation samples unaffected by effluent discharge (Irrigation), irrigation samples affected by effluent discharge (Irrigation down) and paddy field samples (paddy field).

that were similar to those observed for paddy field and irrigation water samples. The highest *E. coli* count for a well sample was recorded at a well in a home that produced tempe (Well 10,  $5.4 \times 10^5$  counts/MPN, Figure 1). The site with the lowest *E. coli* count for both occasions draws its

water from a deeper part of the aquifer that is probably less contaminated (Well 4, Figure 1). The rest of the samples were taken from shallower wells which are closer to septic tanks and more likely to experience high levels of contamination (Goss *et al.* 1998; Krapac *et al.* 2002).

**Table 2** | Water quality for wastewater treatment systems and surrounding waters, Sukunan Village, Yogyakarta

Types of water/wastewater	Water/wastewater quality parameters								
	pH	TSS (mg L <sup>-1</sup> )	BOD <sub>5</sub> (mg L <sup>-1</sup> )	COD (mg L <sup>-1</sup> )	NO <sub>3</sub> -N (mg L <sup>-1</sup> )	NH <sub>3</sub> -N (mg L <sup>-1</sup> )	TN (mg L <sup>-1</sup> )	TP (mg L <sup>-1</sup> )	<i>E. coli</i> (MPN/100 mL)
<b>Wastewater treatment plant effluent</b>									
RBC process									
Wet (December)	7.15	8.0	40.5	84.5	1.0	0.8	173.4	4.8	5.4 × 10 <sup>6</sup>
Dry (August)	7.17	37	88	133.7	0.3	0.3	167.3	4.0	1.6 × 10 <sup>9</sup>
CA process									
Wet (December)	7.08–7.26	12.5	7.5	13.9	1.4	1.4	146.5	0.9	2.4 × 10 <sup>6</sup>
Dry (August)		18	8.2	15.1	2.0	0.03	222.4	0.8	5.4 × 10 <sup>7</sup>
Domestic wastewater effluent discharge standards <sup>a</sup>	6–9	100	100	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
	pH	Turbidity (NTU)*	BOD <sub>5</sub> (mg L <sup>-1</sup> )	COD (mg L <sup>-1</sup> )	NO <sub>3</sub> -N (mg L <sup>-1</sup> )	NH <sub>3</sub> -N (mg L <sup>-1</sup> )	TN (mg L <sup>-1</sup> )	TP (mg L <sup>-1</sup> )	<i>E. coli</i> (MPN/100 mL)
<b>Other water sources in the village</b>									
Well (groundwater)	6.16–7.11	0.06–1.78	1.75–2.92	3.52–10.2	0.33–9.4	0.002–0.18	91.2–263.8	0.067–0.80	8–5.4 × 10 <sup>5</sup>
Irrigation canal	6.84–7.48	13.1–63.5	1.83–5.26	3.52–45.3	0.69–5.21	0.002–1.35	95.5–262.4	0.067–1.37	2.4 × 10 <sup>-4</sup> 2.4 × 10 <sup>10</sup>
Irrigation canal downstream of effluent points	6.89–7.63	9.8–25.8	2.13–3.74	7.04–18.9	0.64–2.66	0.006–1.39	121.4–289.8	0.10–0.71	1.7 × 10 <sup>-5</sup> 1.6 × 10 <sup>7</sup>
Paddy field	–	27.3–77.5	2.05–3.61	7.04–30.2	1.21–1.59	0.023–0.066	109.9–164.6	0.081–0.16	5.4 × 10 <sup>5</sup>
Indonesian Standards for clean water quality <sup>b</sup>	N.A.	5	N.A.	N.A.	10	N.A.	N.A.	N.A.	0 <sup>d</sup>
Indonesian Standards for drinking water quality <sup>c</sup>	N.A.	5	N.A.	N.A.	10	N.A.	N.A.	N.A.	0 <sup>d</sup>
WHO drinking water guidelines	–	–	–	–	11	–	–	–	0
USEPA drinking water guidelines	6.5–8.5	–	–	–	10	–	–	–	0

<sup>a</sup>Peraturan Menteri Kesehatan No. 416 Tahun 1990 Tentang: Syarat-Syarat dan Pengawasan Kualitas Air, Menteri Kesehatan Republik Indonesia. Lampiran II: Daftar Persyaratan Kualitas Air Bersih, R.I. No.: 416/MENKES/PER/IX/1990.

<sup>b</sup>Peraturan Menteri Kesehatan No. 416 Tahun 1990 Tentang: Syarat-Syarat dan Pengawasan Kualitas Air, Menteri Kesehatan Republik Indonesia. Lampiran I: Daftar Persyaratan Kualitas Air Minum, R.I. No.: 416/MEMKES/PER/IX/1990.

<sup>c</sup>Peraturan Menteri Kesehatan No. 416 Tahun 1990 Tentang: Syarat-Syarat dan Pengawasan Kualitas Air, Menteri Kesehatan Republik Indonesia. Lampiran I: Daftar Persyaratan Kualitas Air Minum, R.I. No.: 416/MEMKES/PER/IX/1990.

<sup>d</sup>The Indonesian standards only make reference to total coliform (MPN/100 mL) and not *Escherichia coli*.

\*Nephelometric Turbidity Units.

## BOD<sub>5</sub> and COD

BOD<sub>5</sub> is a common indicator of the presence of polluting organic matter in water. As expected, WWTP effluent has the highest BOD<sub>5</sub> values, varying over one order of magnitude (Figure 2(b), Table 2). Irrigation and paddy field samples had quite similar median values and interquartile

ranges. Low BOD<sub>5</sub> concentrations in well samples show that there is little degradable organic matter in groundwater (Mukherjee *et al.* 2012).

The pattern of COD variation amongst the various sampling locations is similar to that for BOD<sub>5</sub>. Wastewater-treated effluent samples have the highest COD concentrations and the largest variability followed by irrigation canal and paddy field

samples (Figure 2(c)). Well samples have the lowest COD amongst all types of water samples in this study. The outliers for COD and BOD<sub>5</sub> both came from the same location (Well 13, Figure 1). We do not know the cause of the high organic matter at Well 13 but it warrants further investigation.

### Nutrients (nitrate, ammonia, TN and TP)

As expected, WWTP effluent had highest ammonia, TN and TP concentrations compared to the environmental samples taken from the village (Figure 2(d)–(g)). Irrigation samples affected by WWTP effluent had correspondingly high levels of ammonia and TP (Figure 2(e), (g)).

For nitrate, well samples showed higher median value and greater range than even WWTP effluent (Figure 2(d)). The highest nitrate concentrations in well samples came from a temple factory (Well 9, 9.43 mg L<sup>-1</sup>) and a well in a densely populated area (Well 11, 8.37 mg L<sup>-1</sup>) (Figures 1 and 2(d), Table 2). The nitrate levels of irrigation waters and paddy field are higher than WWTP effluent, suggesting an additional source related to fertiliser use. However, the highest nitrate concentration in irrigation waters unaffected by wastewater effluent was taken from a location where irrigation waters from outside enter the village (near Well 4, 5.21 mg L<sup>-1</sup>, Figure 1). This site also had one of the highest TN concentrations recorded for all irrigation samples (262.44 mg L<sup>-1</sup>). The median concentrations for TN are quite similar for all environmental samples except well samples, which had the greatest interquartile variability (Figure 2(f)).

Finally, high TP levels were recorded for well samples when compared to irrigation water samples (Figure 2(g)). Wells with highest TP concentrations are those located in areas with home-based industries (0.798 and 0.315 mg L<sup>-1</sup>, Wells 7 and 8) (Figure 1).

### Comparing water quality between wet and dry conditions

We compared data for wells ( $n = 13$ ), irrigation waters affected by WWTP effluent ( $n = 3$ ) and irrigation waters unaffected by WWTP effluent ( $n = 8$ ) to examine the impact of rainfall seasonality on water quality (Figure 3). The number of samples taken from the wastewater effluent point (two

for each WWTP) and paddy field sites (two locations) are too low for meaningful comparison with other samples.

For the surface water samples, BOD<sub>5</sub>, ammonia, TN and TP are most affected by rainfall seasonality. Median concentrations and variability increase for the December wet season samples (Figure 3). Nitrate shows dilution for the wet season samples for sites unaffected by WWTP due to increasing run-off in irrigation canals after rainfall, but the opposite was observed for affected sites. The increase in nitrate concentration for WWTP affected sites is most likely due to the decreasing performance of both WWTPs in December especially the CA plant (Site 3) (Figure 3(d), Table 1). For ammonia, the seasonal impacts of rainfall are harder to discern due to the unstable nature of this parameter and the interactions between its sources and WWTP treatment performance. The increase in concentrations during the wet season for irrigation sites unaffected by WWTP is most likely due to washing in of animal faeces (e.g. from the centralised cattle area and village areas) via surface run-off into irrigation canals. The decrease in ammonia concentrations for irrigation sites affected by WWTP effluent could be due to oxidation of ammonia into nitrate from increased turbulence of faster flowing waters in the canals. It could also be due to improvements in WWTP treatment performance for the CA system (Site 3), which reduce ammonia loading into irrigation canals (Figure 3(e)).

Well samples exhibited higher median concentrations for *E. coli* and all nutrients during the December wet season (Figure 3). The increased variability observed for *E. coli* and all nitrogen fractions indicates percolation of nitrogen-rich septic tank effluent with infiltration following rainfall. It could also be due to rising water table levels that interact with the septic tanks. This finding is consistent with Smith *et al.* (1999) who recorded increased nitrate concentrations in their well samples during the rainy season.

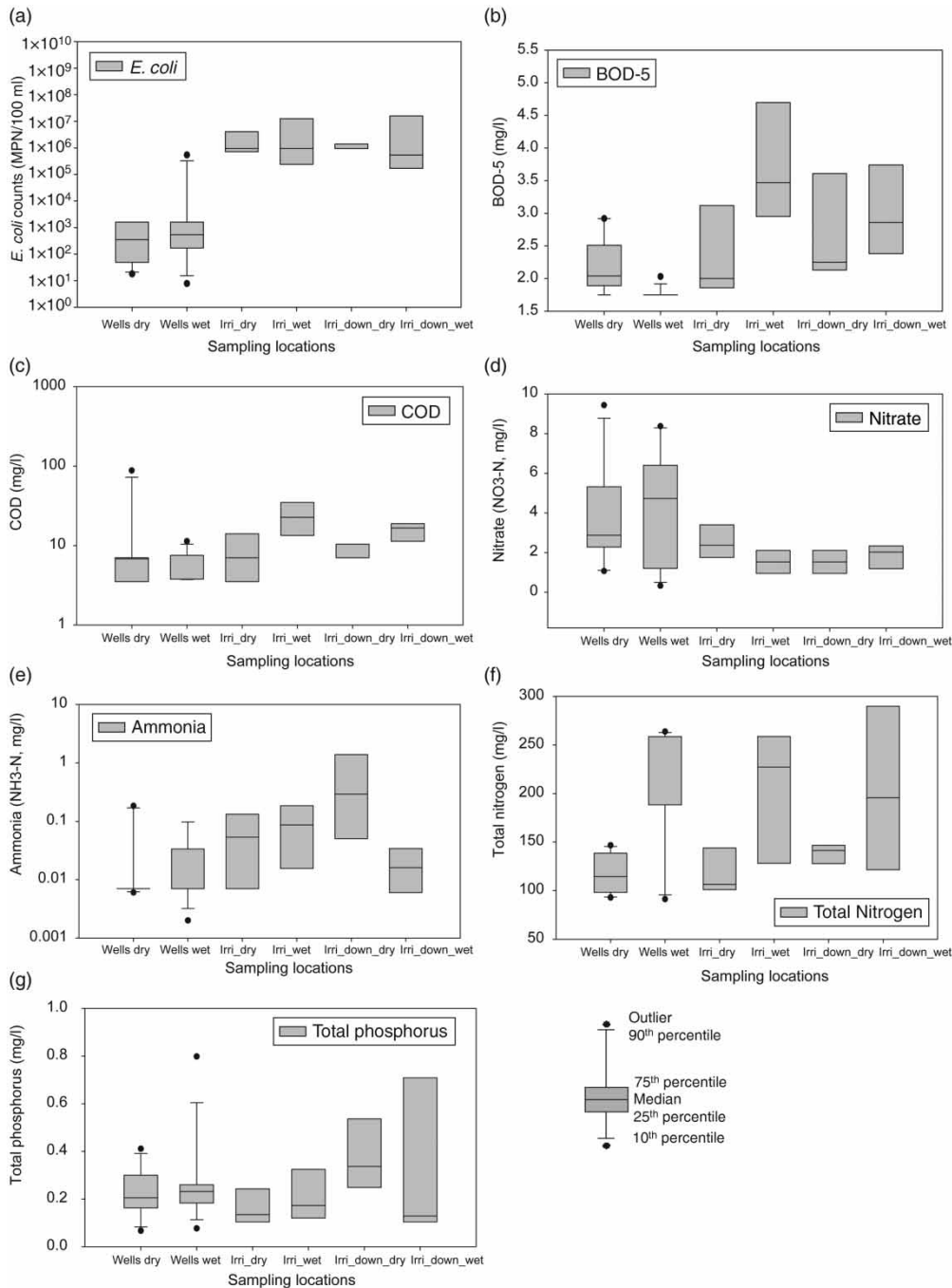
## DISCUSSION

### Extent and source of pollution

#### Surface waters

Water samples from irrigation canals have higher *E. coli*, BOD<sub>5</sub>, COD and ammonia concentrations than well samples.





**Figure 3** | Boxplots of (a) *E. coli*, (b) BOD<sub>5</sub>, (c) COD, (d) nitrate, (e) ammonia, (f) TN, (g) TP for the August (dry) and December (wet) samples for well samples, irrigation canals unaffected by effluent discharge (irr) and irrigation canals downstream of effluent discharge (irr\_down).

The quality of water in paddy fields is similar to that recorded in irrigation canals, especially for parameters such as BOD<sub>5</sub>, ammonia and TN. The discharge of WWTP effluent directly into irrigation canals has an impact on water quality by increasing levels of nitrate, ammonia and TP at sites downstream

compared to unaffected sites. Many surface water samples suffer from nitrate and ammonia pollution because their concentrations are greater than the concentration values found for natural waters (less than 1 mg L<sup>-1</sup>) (USEPA 2012, <http://water.epa.gov/type/rsl/monitoring/vms57.cfm>). However,

they do not pose a threat to human health since nitrate levels are within the WHO and Indonesian standards for drinking water ( $10 \text{ mg L}^{-1}$ , Table 2). The concentration of *E. coli* in irrigation samples exceeded allowable limits. Villagers are at risk of health problems associated with *E. coli* when they come into contact with the bacteria through their daily activities (e.g. washing laundry in irrigation canals and working in paddy fields).

Surface water pollution in this village comes from external and internal sources. External sources are harder to control since they are not within the confines of the village. Village activities such as doing laundry in irrigation canals contribute to elevated TP concentrations from the detergent used. Free-roaming farm animals in irrigation canals and paddy fields contribute nutrients and bacteria. One irrigation sampling site near the CA system (Site 3, Figure 1) recorded high nitrate ( $2.4 \text{ mg L}^{-1}$ ), TP ( $0.25$  and  $0.33 \text{ mg L}^{-1}$ ) and COD ( $20.83$  and  $45.31 \text{ mg L}^{-1}$ ) values on both sampling occasions due to the presence of chickens, and of ducks swimming nearby. Elevated nutrient concentrations in irrigation waters also comes from washing in of organic fertilisers (compost and manure) into irrigation canals, and from WWTP effluent discharge (Table 1).

### Subsurface waters

Groundwater samples are contaminated with high levels of nitrate, TN and TP (Figure 2). Some samples have concentrations that were comparable to WWTP effluent. Current nitrate levels in groundwater samples range between  $0.33$  and  $9.4 \text{ mg L}^{-1}$  and fall within Indonesian and international standards for drinking water quality, with the exception of two wells which have values close to the limit (Wells 8 and 10, Table 2). Consuming water from these wells will have negative health impacts on the villagers in the long run and should be avoided. On a broader scale, nitrate contamination of groundwater in the Sukunan Village is relatively low compared to a nearby village 3 km away where well waters had concentrations over the  $10 \text{ mg L}^{-1}$  limit (Smith *et al.* 1999).

Groundwater TN concentrations ( $91.2$ – $263.8 \text{ mg L}^{-1}$ ) from the Sukunan wells are comparable to the concentrations observed for samples from two WWTPs in the village and higher than the concentrations expected from septic tank

effluent ( $40$ – $100 \text{ mg L}^{-1}$ ) (USEPA 2008). This suggests that wastewater is not the only source of nitrogen in our groundwater samples. The high TN values in our samples with correspondingly low nitrate and ammonia concentrations shows that the organic form dominates TN. The high concentrations and variability of nitrate and TN concentrations suggest that localised sources cause some areas to be more contaminated than others (Figures 2(d) and 2(f)). These sources could be active septic tanks (especially in more densely populated areas of the village, Well 11) or areas where fertilisers are applied and leached into the local aquifer (e.g. Long & Sun 2012). Further, certain hotspot contamination areas such as the tempe factories show greater groundwater contamination (Wells 8 and 10, Figure 1). Water samples taken from these locations also had consistently higher TN, TP and COD concentrations. Liquid wastes from tempe production had high BOD ( $348 \text{ mg L}^{-1}$ ), COD ( $535 \text{ mg L}^{-1}$ ) and nutrient content (e.g. carbon, nitrogen, potassium, magnesium and phosphorus) (Chaerun 2009; Wignyanto & Ariningrum 2012). These wastes are treated at the municipal WWTPs but soil and groundwater pollution can still occur via leaking pipes and spillage onto, and/or washing of, the earthen dirt floors where production takes place.

The TP concentrations found in Sukunan well samples range between  $0.067$  and  $0.8 \text{ mg L}^{-1}$ . We cannot compare our results with a benchmark since there are no drinking water quality standards for TP set by international agencies or the Indonesian government. But our sample concentrations fall within the range expected for WWTP effluent in the USA ( $0.1$ – $1.1 \text{ mg L}^{-1}$ ) and are much lower than typical septic tank effluent ( $3$ – $40 \text{ mg L}^{-1}$ ) (USEPA 2008; Lowe *et al.* 2007 cited in Lusk *et al.* 2011; Withers *et al.* 2011). The lack of orthophosphate data precludes us from analysing the effect of septic tank effluent on groundwater quality especially since the effluent has high levels of orthophosphate or soluble reactive phosphorus (Jarvie *et al.* 2010).

*E. coli* counts in all well samples exceed international and Indonesian drinking water standards (Table 2). *E. coli* in groundwater comes from septic tank effluent and cattle manure in the village (Goss *et al.* 1998; Krapac *et al.* 2002; Budisatria *et al.* 2007; Rawat *et al.* 2012). Groundwater of this village may also be affected by regional groundwater pollution from the widespread use of septic tanks in the Yogyakarta region (Smith *et al.* 1999; Budisatria *et al.*

2007). The practice of boiling well water before consumption is sufficient for the time being since there have been no recent outbreaks of gastroenteritic diseases in the village. Projected population increase in this village and its immediate surroundings may require the villagers to use more sophisticated methods of water disinfection.

### Impact of the WWTPs on water quality

Comparison of our findings with available data from small community-based WWTPs indicates that the two Sukunan WWTPs perform better in removing solids (TSS) and oxygen-demanding wastes from wastewater (BOD<sub>5</sub> and COD) (see Table 1; Foley *et al.* 2001). The differences in treatment performance could be due to differences in the design and quality of materials used in the WWTP construction. The Sukunan WWTPs, however, released nutrients, particularly nitrate, ammonia and TN, and *E. coli* into surface waters of the village (Figure 2). Although efforts by the villagers to move cattle to a centralised location help reduce the loading of nutrients and oxygen-demanding wastes into irrigation canals, the inconsistent and poor nutrient removal efficiencies of the two WWTPs investigated nullify the reductions in nutrient loading achieved from relocating the cattle. The nutrients from WWTP effluent discharged into irrigation waters seem to have a beneficial effect on paddy yield, according to some villagers. Standing waters in the village receiving irrigation waters show the negative impacts of water quality where signs of eutrophication and mosquito breeding are evident.

### Suggestions to improve water quality in the village

The groundwater and surface waters in this village suffer from pre-existing pollution caused by septic tanks and agricultural activities. The role of septic tanks in groundwater pollution in these villages cannot be ignored given an increase in demand for such systems with a rising population in Indonesia (Smith *et al.* 1999; Budisatria *et al.* 2007; Sngun *et al.* 2010). In developed countries, techniques to reduce the impacts of septic tank discharge include improvements in their design and careful site selection followed by rigorous maintenance of existing systems. Implementing rigorous maintenance can be a major challenge even in developed

countries for a variety of reasons including insufficient knowledge and unclear roles of government agencies and the home owner (Butler & Payne 1995; Harrison *et al.* 2012). In a village like Sukunan, septic tanks are still the most affordable means of treating domestic wastewater. The separation distance of 10 m between septic tanks and wells does little to prevent groundwater contamination in this dense housing configuration, especially if septic tanks are poorly maintained and leaking (Jarvie *et al.* 2010; Habteselassie *et al.* 2011; Macintosh *et al.* 2011).

Pollution from septic tanks can be reduced if more village households are connected to the five WWTPs since these systems have not reached their maximum capacity of 50 to 150 households depending on design and individual household population (Foley *et al.* 2001). One obstacle to increased household connections to WWTP is the inability of poorer villages to meet the pipe installation costs and the monthly operation charge (3000 Rupiah, approximately 0.31 US dollars). At present, part of the cost of WWTP connection is borne by the wealthier villagers. Part of the money could also come from the profits gained from selling the village municipal waste and compost produced in the village. Sales of these goods can be improved with better marketing and price negotiations with the help of NGOs or private companies.

The treatment performances of the existing WWTPs have to be improved in order for increased connections to have a positive impact on surface and subsurface water quality in this village. Future work in this village includes an examination of the reasons behind the current poor WWTP performance so that design improvements can be made to reduce nutrient loadings into the irrigation canals.

The impact of tempe industries in the village is serious and needs to be addressed by first monitoring the quality of tempe wastewater from the individual home factories. It is possible that the WWTP systems, such as Systems 4 and 5, are overloaded due to the addition of tempe wastewaters (Figure 1). The set-up of the home industries can be improved by sealing off the ground surface to prevent seepage. Separate treatment systems may be needed to pre-treat the wastewater before channelling them to the existing WWTPs.

It is also important to study the impact of organic fertiliser application on water. The chemical characteristics of commercial and home-made fertilisers used in this village and elsewhere in the vicinity needs to be evaluated. Ways

to reduce leaching from organic fertiliser include washing the compost artificially before application, stepwise application of compost over time to reduce the nutrients available for leaching, and timing fertiliser application to dry periods to reduce leaching of the fertiliser (Christensen 1983). We are not sure how these methods might be adapted to suit the Sukunan agricultural practices and further research in this area is needed.

For community-based efforts at Sukunan to benefit the village in the long run, the villagers need strong collaborations between NGOs, local governments, academic institutions and even private companies. NGOs play an important role as information providers and act as important links between the village community, local governments and technical institutions. As the nature of the environmental problem changes or requires improvements, villagers need to draw upon the expertise, networks and financial help of these organisations (Padawangi 2010; Sansom 2011). There are many examples of successful collaborations between NGOs and villagers in setting up and managing community projects in the literature (e.g. Kyessi 2005; Sansom 2011). In this study, the local NGO Yayasan Dian Desa already provides important technical advice on the WWTPs for the villagers. The local university, Gadjadara University, sends students to carry out simple monitoring of the WWTP. These activities could be extended to include villages in monitoring activities using simple field kits and facilitated by local NGOs (e.g. Bruhn & Wolfson 2003).

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## CONCLUSIONS

This study provides an initial assessment of water quality in the Sukunan Village by examining wastewater and water samples from different locations within the village. Our findings show that the WWTPs have a limited effect on improving village water quality. Oxygen-demanding wastes from sewage are removed by the WWTPs but these systems did little to remove nutrients from sewage. The RBC system failed to remove ammonia and TN on both sampling occasions while the CA system failed to remove nitrate on both sampling occasions. Removal efficiencies of both systems were also variable over time. There are times in the

year when pollution is higher due to variable WWTP performance or rainfall. Rainfall tends to increase the concentrations of nutrients in irrigation canals and wells but the impact of rainfall is complicated by WWTP discharge into irrigation canals.

Despite the construction of the WWTPs, we found that irrigation waters still had high levels of *E. coli* and oxygen-demanding wastes which could originate from village animals and farming activities. Well samples had high *E. coli* counts, and nitrate and TN, which originate in active septic tanks, small-scale industries and fertilisers used in the village. Therefore, sources of pollution include both internal and external sources despite efforts by the villagers to control pollution within the village. External sources of pollution are beyond the villagers' control and highlight the wider problem of water pollution in the Yogyakarta region.

All the samples fell within recommended drinking water standards for nitrate and *E. coli* set by both international agencies and the Indonesian government with the exception of two wells which had nitrate levels close to the drinking water limit. The villagers are at risk from health problems associated with ingesting *E. coli* and nitrate from well water, and coming into contact with *E. coli* through their farming activities.

To improve water quality in this village, the villagers should try to increase the number of households connected to the WWTPs, while at the same time request a more thorough investigation of the WWTPs to find out the reasons behind their poor nutrient removal performance. We cannot identify the cause of poor nutrient removal from two sampling occasions. Poor performance could be due to design problems or due to system overloading, perhaps from the tempe industries. In this respect, there is also a strong need to examine the role of tempe industries in the village in water pollution since these home-based industries are common in Indonesian villages.

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