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Sustainable decentralised sanitation using duckweed-based ponds

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HIGH OPERATIONAL AND construction costs, mechanical complexities, personnel requirements, and foreign currency and electricity shortages have rendered high-tech wastewater treatment technologies unattractive in developing countries. Serious water quality problems and wide acceptance of the value of nutrients in municipal sewage have made the resource recovery concept a new guideline in novel wastewater treatment systems (Gijzen, 1998). This concept implies that wastewater is managed at the lowest possible level where it is rendered safe for nutrient reuse in agriculture. Natural systems have increased opportunities in this direction.

In Zimbabwe, research is on-going on the use of constructed wetlands, urine separation, and duckweed-based pond systems (DPS) for onsite and small community (decentralised) treatment of sewage. This paper focuses on the performance and operational problems at two full-scale duckweed-based systems in the Masvingo province of Zimbabwe. A monitoring study of these ponds was done from September 2000 to March 2001 focusing on wastewater treatment efficiency, duckweed production, and duckweed application. This paper focuses on nitrogen and phosphorous as the main parameters.

Duckweed systems in Zimbabwe

Duckweeds have a worldwide distribution with the dominant species in Zimbabwe being *Lemna Perpusila torr* and *Spirodella Punctata* of the six species identified (IWSD, 1996). *Lemna minor* has been used for wastewater treatment in Zimbabwe and was found to have a protein content of 28% of dry matter (Kusina *et al.*, 1999). The nutrient value of duckweed is variable (30–49% protein content) depending on species, conditions of its environment, stage of growth, and probably processing procedures (Huque *et al.*, 1997; Caicedo *et al.*, 2000). Pilot studies on DPS were started in 1996 by the Institute of Water and Sanitation Development (IWSD). An average duckweed yields of 53 g/m².d were realised compared to recommended figures of 100 g/m².d (Chidavaenzi 1996, Gijzen 1997), with the yield lowest in winter. The high concentration of NH₄ throughout the DPS was noted in the pilot studies and seems to have persisted in the full-scale plants as well. The concentration of free ammonia (NH₃) is dependent on temperature and pH and can be toxic to aquatic life at higher concentrations (Caicedo *et al.*, 2000). In Australia concentrations above 60 mg N/l were found to be toxic perhaps due to high levels of free ammonia in the water (FAO, 1999).

The pilot scheme used a retention time of 20 days which was later changed to 35 days after problems with ammonium removal. However, nutrient removals were much higher for DPS than waste stabilisation ponds (1.5 times for PO₄ and 1.2 times for NH₄) at the same site. pH ranges of 7–8 were achieved which precluded algal growth and subsequent free ammonia production.

A project on two full-scale DPS was started in June 1999 by IWSD at Nemanwa and Gutu growth points in the Masvingo province of Zimbabwe. These centres have respective populations of 8 000 and 15 000 (IWSD, 1999). Bamboo floating booms sub-divide the ponds into 15 m by 20 m bays and help in controlling wind effects. Duckweed was harvested from the sub-divisions at the rate of 80–160 kg/ha.d (wet weight) and this was increased to 190 kg/ha.d for Nemanwa because of the low influent volume and fears of the duckweed dying due to exhaustion of nutrients. The duckweed is dried in sheds covered with a shed cloth to allow a limited amount of light to penetrate and a perforated, raised floor allows the draining of water. Air drying in the shade takes four days and sun drying on a black plastic sheet takes six days. After drying, the duckweed is weighed and stored in 50 kg bags ready for use as chicken feed.

At Nemanwa the chicken project is run by the youth whilst at Gutu it is based at a nearby school. The chicks are fed on a conventional broiler starter for the first four weeks after which they are put on a diet with varying proportions of duckweed (0%, 10% and 20% duckweed by weight). Similar to findings by Huque *et al.* (1997), tests at the University of Zimbabwe confirmed that duckweed can be incorporated in broiler ration up to 10% level without compromising growth performance or carcass composition (Kusina *et al.*, 1999). Samples sent for broiler performance and microbiological analysis also confirmed that the chickens from both centres were suitable for human consumption (IWSD, 2000). At Nemanwa a vegetable gardening project was started in 2000 using chicken droppings and excess dried duckweed as manure.

Materials and methods

A sewage quality monitoring scheme was established for the two DPS in Masvingo. The ponds layout and sampling locations are shown in Figure 1. These ponds were originally designed as algae-based waste stabilisation ponds and no structural modifications were done to suit duckweed pond design criteria. Possible advantage of the Gutu anaerobic pond design is that peak loads of ammonia can be accommodated by its large volume. Masvingo is generally a dry

place with temperature ranges of 15 – 32°C and average rainfall of 620 mm.

In studies by the IWSD some of the parameters measured are NO₃, PO₄, BOD_{total}, and COD_{total}. In this study, additional parameters to characterise nutrient flows and develop future mass balances are NO₂, NH₄, TKN, TP, DO saturation and flow. In addition, pH, temperature, conductivity, turbidity and DO concentration were measured in the field. All samples were collected and analysed monthly according to standard methods (APHA/AWWA/WPCF, 1992). Sampling results for September 2000 to March 2001 based on each unit within the treatment system are reported. The study also focused on filtered and unfiltered samples as previous studies by IWSD had made conclusions at the exclusion of COD and nutrients content in suspended organic matter in the effluents. However, this strategy was frequently hampered by field logistics. Between November 2000 and January 2001, there was a complete die-off of the duckweed. The monitoring scheme then included KweKwe City where duckweed had just been introduced and the respective water qualities were compared in trying to establish the cause. NH₄ was then re-introduced in the analysis as free NH₃ poisoning was suspected.

Results

The analytical results for the monitoring period shown in Table 1 below reveal an excessively high TN content in influent at Nemanwa. At Gutu, where there was no water rationing, the TN concentration is reflective of TN production of 8 g/c/d and wastewater production rate of 80 lcd (JICA, 1996). There was a gradual rise in TN concentrations over the monitoring period for Nemanwa and Gutu plants. Nitrogen levels in both systems were rising up to January and thereafter seemed to be influenced by rainstorms as shown in Figures 2 and 3 below. These graphs also illustrate nutrient removal patterns for each

plant and for each month. TN was illustrated in logarithmic scale because of the wide variation in levels.

Ammonium nitrogen (NH₄-N) was measured in September 2000 and only resumed after duckweed die-off in February 2001. In September 2000 this covered only Gutu Raw (5.3 mg/l) and effluent 3.7 mg/l), and twice for Nemanwa Raw (average 7.4 mg/l). There seemed to be a general trend in the rise of ammonia in the ponds up to February 2001. A decrease in NH₄-N levels in March 2001 coincided with the re-establishment of the duckweed. The ponds in KweKwe were also struggling in February but also peaked up in March when NH₄-N levels decreased substantially.

COD removal was calculated based on total COD for raw sewage and filtered COD for effluent. This averaged 45% for Gutu and there was no effluent at Nemanwa. Previous results by IWSD (2000) show that effluent COD and BOD have been consistently above limits especially in the June to December period. Conductivity was very high at averages 925±164 mS/cm for Nemanwa and 883±117 mS/cm for Gutu. pH ranged 7.2 to 8.5 and DO levels on one day reached super-saturation levels of 20 mg/l in the afternoon hours but averaged 7.7 mg/l. Duckweed is believed to grow well in pH ranges of 5.9 – 7.4, whereas extreme pH may cause direct growth inhibition, independent from ammonia effects (Caicedo *et al.*, 2000 after Landolt, 1987).

Discussion

A nitrogen removal efficiency of 88% was achieved up to end 1 at Nemanwa and 62% at Gutu. Higher nitrogen removal efficiencies can be achieved at low influent N concentration (Rijal, 1999). Phosphorous removal was very poor at 35% at Nemanwa and none at Gutu. Nitrogen removal efficiency was a very high % at Nemanwa in the rainy season but this trend was not observed at Gutu. In some cases the results showed higher concentrations in effluent than in raw sewage - this anomaly can be overcome

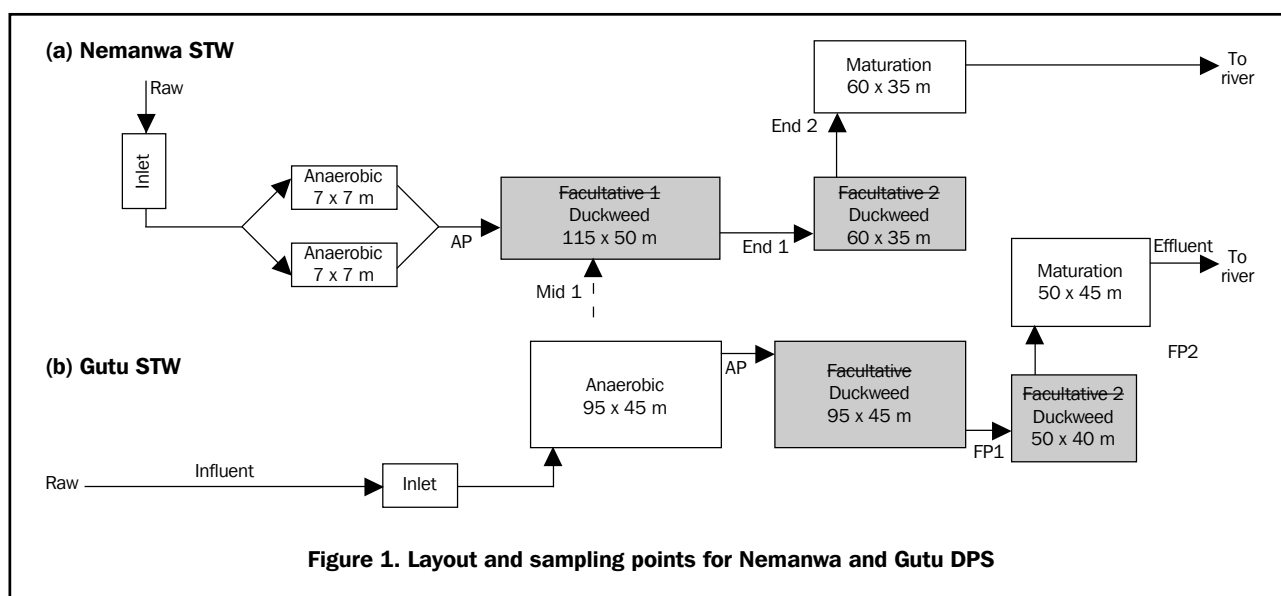


Figure 1. Layout and sampling points for Nemanwa and Gutu DPS

Table 1. Monitoring results for September 2000 to March 2001

Description	Sampling Point	Number of Samples	TN		TP	
			mg/l	STDEV	mg/l	STDEV
Nemanwa						
Influent	Raw	7	352.5	547.7	3.5	1.82
Anaerobic Pond	AP	6	276.4	264.3	3.0	1.26
Middle of facultative pond 1	Mid 1	1/2 *	28.5	-	1.7	0.2
End of facultative pond 1	End 1	6	42.1	66.4	2.2	1.1
End of facultative pond 2	End 2	1 **	3.4	-	1.0	-
Efficiency %, Raw to End 1			88		35	
Gutu						
Influent	Raw	5	98.7	144.9	2.1	0.6
End of anaerobic pond	AP	5	88.4	83.6	2.4	0.8
End of facultative pond 1	FP1	5	78.3	105.6	5.9	7.5
End of facultative pond 2	FP2	5	88.3	92.1	4.0	0.7
Final effluent	Effluent	6	37.9	33.6	2.5	0.8
Efficiency %, Raw to Effluent			62		0	

* 2 samples for TP and 1 sample for TN - results show bias from few readings

** Water only started flowing into this pond in March 2001

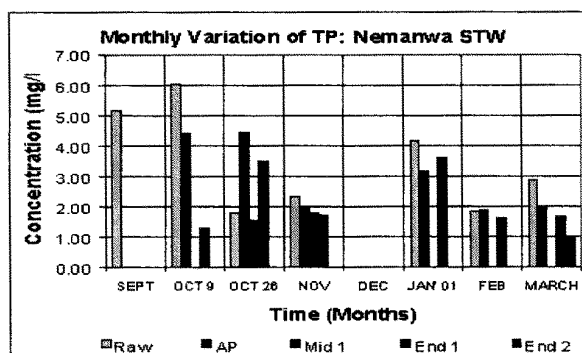
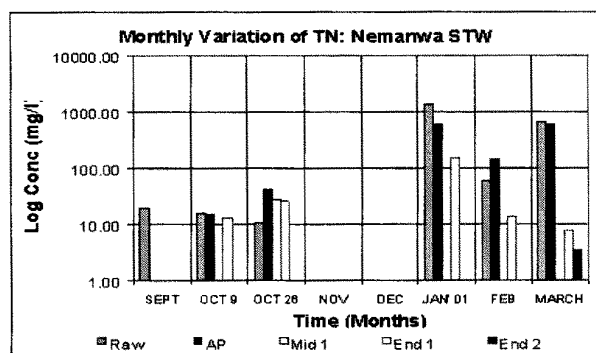


Figure 2: Monthly variations of nutrients at Nemanwa Sewage Treatment Works

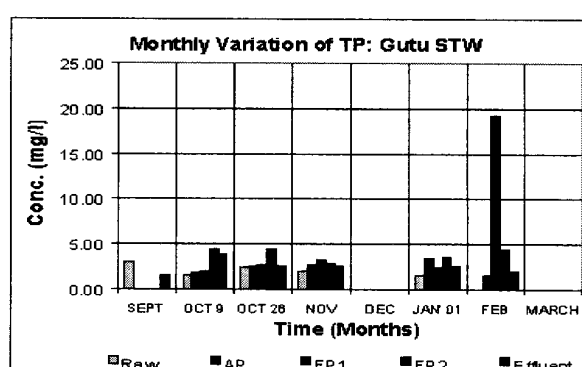
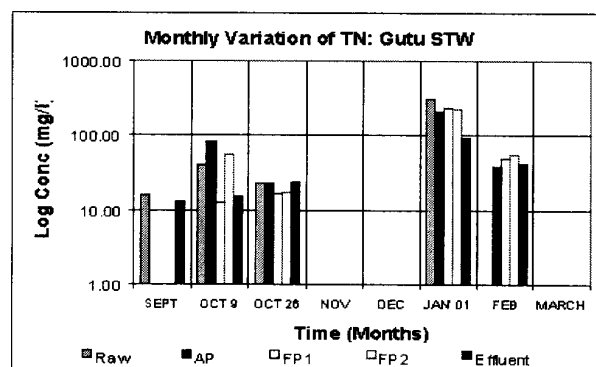


Figure 3: Monthly variations of nutrients at Gutu Sewage Treatment Works

by collecting composite samples over many hours per day (ideally 14 hrs). It is also possible that samples were affected by agitation of water during harvesting or the nutrients became concentrated due to excessive evaporation in the area. Sampling can be done just before harvesting to remove agitation effects.

The sewage at both Nemanwa and Gutu is composed of predominantly domestic sewage. This rules out heavy metals as the cause of the observed duckweed die-offs. Ammonium concentrations and pH values in typical domestic wastewater studied may severely reduce duckweed growth. In laboratory experiments by Caicedo *et al.* (2000), duckweed died at 50 – 100 mg/l NH₄-N when pH fluctuated between 7.4 and 9.0. The influent levels of TN at Nemanwa were also very high (Table 1), consistent with concentrations from high temperature areas and low water usage imposed by water rationing. The TN levels at Gutu were within the lethal range whilst at Nemanwa the inflow into the duckweed-covered lagoon (FP1) was too high at 276.4 mg N/l. Nutrient and COD removal seems to be affected by the design of the ponds which allows short-circuiting and have large depths of 1.5 m. Ideal depths for DPS are 20 - 50 cm with plug flow conditions (Gijzen, 1997). The short circuiting is a result of large pond size or siting of inflow/outflow as shown in Figure 1. The use of shallower depths would also increase duckweed production areas and land cost is not a major item at such small centres. The design of the anaerobic ponds for both plants were not optimised and suitable depths of about 4 m are required compared to the installed depths of <1.5 m. The current harvesting rates of 80 - 190 kg/ha.d (low) can affect yields and should be about 500 - 600 kg fresh weight/ha.d (Gijzen, 1997). IWSD suspected nutrient depletion at Nemanwa and went on to control harvesting in the dry season based on this fear. The sampling results in this study reveal a nutrient built-up. This needs to be further confirmed by constant monitoring of flows and pollution loads resulting in a nutrient mass balance.

Conclusions and recommendations

DPS, when properly designed and operated, have a high potential of removing COD and nutrients with added socio-economic benefits at small sewage treatment works although the pilot systems in Zimbabwe did not fully support this notion. This was due to the design aspects of the ponds as they were originally designed as algae-based waste stabilisation ponds. Special problems related to inappropriate pond depths of about 1.5 m, design defects of the anaerobic ponds, and short-circuiting. Recycling of effluent back to the inlet works may also be required to dilute the influent and improve performance. The design of duckweed-based pond systems needs to be adjusted to the influent ammonium concentrations, pH value and buffering capacity. The harvesting of the duckweed and hence the stocking density, needs optimisation. The feeding of duckweed to chickens needs to be kept within 10% of the conventional chicken feed to avoid compromising growth performance and carcass composition. The reuse potential

of duckweed can be further enhanced by using chicken droppings and composted excess duckweed as manure as is presently happening at Nemanwa.

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