Performance Assessment of Full-Scale Decentralised Wastewater Treatment Systems (DEWATS) in India

A. Bugey*, S. Sinha*, N. Reynaud**, C.A. Buckley***, R. Pradeep*

*CDD Society, # 621, 5th Main Road, OMBR Layout, Banaswadi Post, Bengaluru 560 043, INDIA
(Email: *bugey@borda.de; susmita.s@cddindia.org*)
** Bremen Overseas Research and Development Association (BORDA), Fahrenheitstr. 9, 28359 Bremen, GERMANY
(Email: *reynaud@borda.de*)
*** University of KwaZulu-Natal Durban/South Africa, Pollution Research Group
(Email: *BUCKLEY@ukzn.ac.za*)

Abstract
This study aims at the assessment of long-term performance of three full-scale Decentralised Wastewater Treatment Systems (DEWATS) by analysing monitoring data of six years. A second objective is to provide recommendations for improved wastewater monitoring. All studied plants are located in India.
The performance of the DEWATS was analysed mainly regarding removal of Chemical Oxygen Demand (COD) concentrations. All plants comply with the Indian COD discharge standard. COD concentrations and calculated removal rates show high variation at all treatment steps. However, statistical analysis indicates significant reduction of COD concentrations for most treatment modules. No constant increase or decrease of treatment capacity over the years is observed. Critical performance levels are not reached.
The variation in the data cannot be fully explained from the existing information. Attribution to single influencing factors should be subject to further research. The assessment shows that non-technical aspects (e.g., social and management factors) should be included in the monitoring programme in order to facilitate interpretation of the data.

Keywords
Decentralised Wastewater Treatment Systems; Performance Assessment; Wastewater Monitoring

INTRODUCTION

Water resource pollution by human wastes has become an increasingly alarming problem especially in many developing countries, where treatment of wastewater is often insufficient (United Nations Development Programme, 2006). Decentralised Wastewater Treatment Systems (DEWATS) as described by Ulrich *et al*. (2009) provide a low-maintenance treatment option for small communities. Experience shows that specific locations require their own design and implementation approach. This in turn is assumed to impact the performance of the unit. Most previous studies on DEWATS performance have been conducted on plants operating at laboratory or pilot scale under ideal conditions (e.g., Bodkhe, 2009; Foxon, 2009). However, real settings often differ from ideal ones in terms of varying feed characteristics and volume as well as social factors. The data-set analysed in this paper is one of the first to cover long-term monitoring results of full-scale DEWATS plants located in India.

This study has two main objectives. The first one is to assess the long-term monitoring data of three full-scale DEWATS regarding trends in performance and compliance to discharge standards. The second objective is to give recommendations for improved wastewater monitoring.

Decentralised Wastewater Treatment Systems

Decentralised small scale options, like DEWATS, are characterised by low operation and maintenance (O&M) requirements. The flexibility and simplicity of the approach makes DEWATS a valuable alternative to high technology solutions in remote locations, e.g., in peri-urban areas of rapidly growing cities in many developing countries. Use of energy is normally not required for operation. DEWATS plants consist of modules performing at different stages of the treatment process: primary treatment in a septic tank (ST) or a biogas settler (BGS), secondary treatment in an anaerobic baffled reactor (ABR) and/or anaerobic filter (AF) and tertiary treatment in a planted gravel filter (PGF) and/or polishing pond. DEWATS at different project sites have varying site-specific configurations of the modules. More information on DEWATS can be found on the homepage of Bremen Overseas Research and Development Association (2011).

MATERIAL AND METHODS

The Plants

Three DEWATS units have been monitored approximately every 6 months since 2003 (Plant 1 and 3) and 2004 (Plant 2), respectively. The monitored plants represent different application sectors: a community sanitation centre, a hotel and a home for people with disabilities (Table 1). All modules of the plants are designed based on the criteria elaborated by Sasse (1998).

Table 1. Overview of the studied DEWATS. (BGS = Biogas settler; ST = Septic tank; WW = Wastewater; BW = Blackwater; ABR = Anaerobic baffled reactor; AF = Anaerobic filter; PGF = Planted gravel filter)

	Plant 1	*Plant 2*	*Plant 3*
Sector	Home for people with disabilities	Community Sanitation Centre	Hotel/Restaurant
Year of construction	2002	2003	1999
Feed type	Toilet, shower, laundry and kitchen WW	Toilet, shower and laundry WW	Toilet, shower, laundry and kitchen WW
Monitoring period	2003 – 2010	2004 – 2010	2003 – 2010
Design values			
Wastewater generated [m^3/d]	9	11.5	25
User numbers	70	750	200
Actual values			
Wastewater generated [m^3/d]	8.2	ca. 9	NA
User numbers	ca. 40 inhabitants until 2009, ca. 90 from 2009	ca. 600 users/day, some days up to 1000	ca. 200 users/d
Modules			
Primary treatment	BGS	2 BGS	Oil Separator, Grease Trap, ST (only BW & kitchen WW)
Secondary treatment	ABR (16 chambers)	ABR (12 chambers)	ABR (6 chambers) + AF(2 chambers)
Tertiary treatment	PGF	PGF	PGF + Polishing Unit

Sampling and analytical methods

Grab samples were taken approximately every six months at the inlet and outlet of each module. On each sampling date two sampling rounds were carried out. The analysed parameters were chosen in order to check if discharge standards are met and to assess the performance of the monitored DEWATS. Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD_5), Total Suspended Solids (TSS) and Phosphorous were analysed by certified external laboratories using Standard Methods (Standard Methods for the Examination of Water and Wastewater, 1998). Additionally, pH and the general physical condition of each plant were recorded. An O&M database was compiled for the three DEWATS units.

Limitations

DEWATS serving small communities and sanitation centres generally show large variations in diurnal and long-term hydraulic and load feed-characteristics. Wastewater monitoring activities of DEWATS are influenced by some practical limiting factors listed by Reynaud *et al*. (in press). Keeping these limiting factors in mind, the data is analysed to establish performance trends.

Calculation of loads would be the desirable methodology for data analysis. However, flow measurements have not been part of the performance monitoring carried out for this study because of the given conditions. Therefore, hydraulic and organic load of the wastewater has not been calculated. It is assumed that due to the design, construction and flow arrangements in the DEWATS modules, no major fluctuations in the quantity of flow takes place.

Data analysis

The performance assessment in this paper is based on COD concentration analysis. As a first step feed concentrations are compared to literature values. Compliance with the Indian national discharge standards of 250 mg/L (Environment Protection Rules, 1986) is assessed. Significance of reduction in COD concentrations from one treatment module to the next is analysed with Students t-test. Fluctuations in the data are compared to the available information on external factors such as O&M status (desludging, change of filter material in the PGF, by-passing of some treatment modules), user numbers, availability of water as well as field precipitation observations.

RESULTS AND DISCUSSION

Data variation

All plants show a high variation between monitoring dates. The variation can be subdivided into different categories:

i. <u>Temporal variation</u>: Each sample represents only the moment of sample taking. High variation exists between monitoring dates.
ii. <u>Spatial variation</u>: High variation within one compartment may exist and sample might not represent the whole compartment. This is due to the fact that reactors are not homogenized and should be more relevant for the first compartments.
iii. Possibly, <u>measurement errors</u> during lab analysis.

Especially sampling of the inlet to the plants is subject to high variation as the characteristics can vary within minutes. The representativity of the feed samples is highly dependent on the set-up of the inlet. As a consequence of this high uncertainty of sampling, the values of the inlet at the plants have to be treated with care.

Field Data Interpretation

Plant 1. The sampling set-up of this plant only allows taking samples from the inlet pipe of the register to the first treatment module. Therefore, the measured values represent only the moment of sample collection. The measured COD concentrations of the feed are relatively low (Table 2) compared to typical values of domestic wastewater (Veenstra *et al.*, 1997) and expected values based on a onetime assessment of wastewater flow and user numbers as well as the general average per capita COD production in India (Sasse, 1998). According to this calculation the feed COD concentrations should be around 825 mg/L. BOD concentration measurements show close correlation to the COD concentrations as expected. Average TSS values decrease through the consecutive treatment modules. As stated in other publications (e.g., Ulrich *et al.*, 2010), Phosphorous does not decrease. The standard deviations of all parameters are high at all sampling points.

The discharge standard for COD of 250 mg/L is already met at the ABR inlet for all sampling dates. However, other parameters require further treatment. The pH at this plant is almost always above at 6.5 or above signifying that anaerobic digestion takes place (Speece, 1996).

Table 2. Average COD, BOD, TSS and Phosphorus concentrations at Plant 1. (CV = Coefficient of Variation; ABR Dist. = ABR Distribution Chamber)

	COD		BOD		TSS		Phosphorus	
	Average [mg/L]	CV [%]	Average [mg/L]	CV [%]	Average [mg/L]	CV [%]	Average [mg/L]	CV [%]
BGS Inlet	263 (±135)	51	96 (±58)	60	87 (±54)	62	17.0 (±11.5)	68
ABR In	145 (±47)	33	51 (±24)	46	91 (±80)	88	17.4 (±8.0)	46
ABR Dist.	88 (±29)	33	33 (±15)	45	51 (±54)	105	17.5 (±6.8)	39
PGF Inlet	68 (±31)	46	24 (±13)	53	43 (±56)	132	22.4 (±10.7)	48
PGF Outlet	45 (±28)	62	14 (±6)	45	24 (±19)	80	28.5 (±33.4)	117
Collection tank	46 (±34)	74	14 (±11)	79	28 (±31)	110	22.8 (±26.1)	114

None of the sampling points shows any pattern or trend in performance over the monitoring period (Figure 1). Therefore, the data can be analysed using averages. Moreover, the variations observed in the data do not follow a pattern.

Figure 2 shows the decrease of COD concentration means from one module to the next. Statistical analysis confirms significant decrease of the COD concentration means for almost all treatment steps. Only the collection tank does not decrease COD concentrations significantly (Figure 2). Calculation of removal rates shows a high overall removal, even if calculated with the low inlet values measured. The removal rates for BGS, ABR and PFG are 32 (±28), 54 (±16) and 34 (±18), respectively (Table 3).

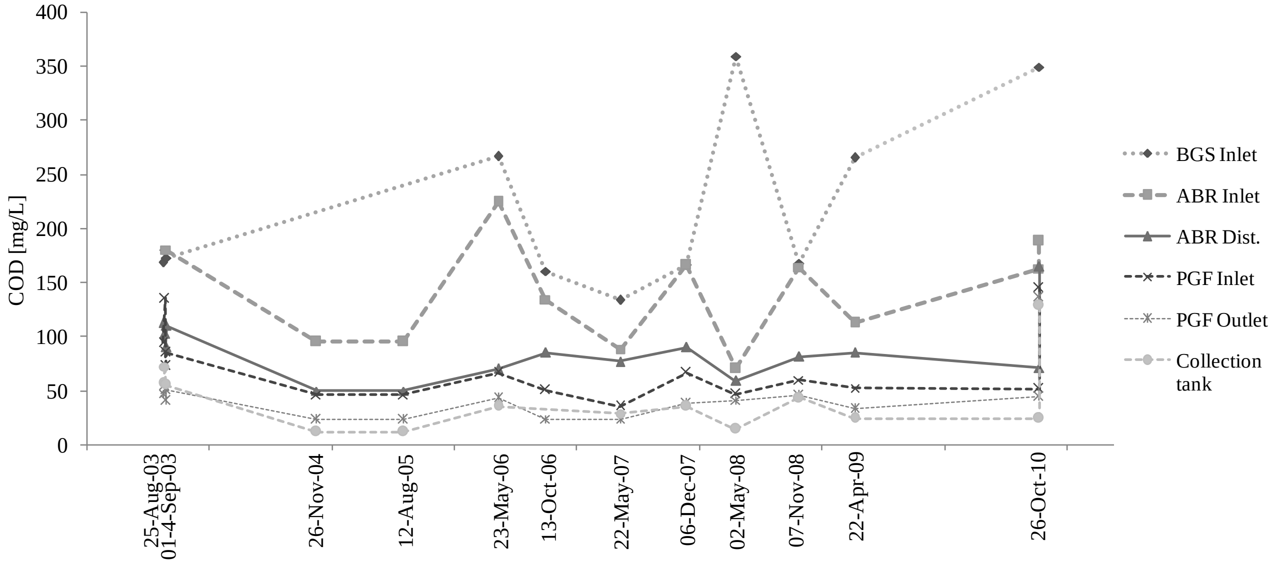

Figure 1. COD concentrations at Plant 1. Each data shows the average from two monitoring rounds. (ABR Dist. = ABR Distribution Chamber)

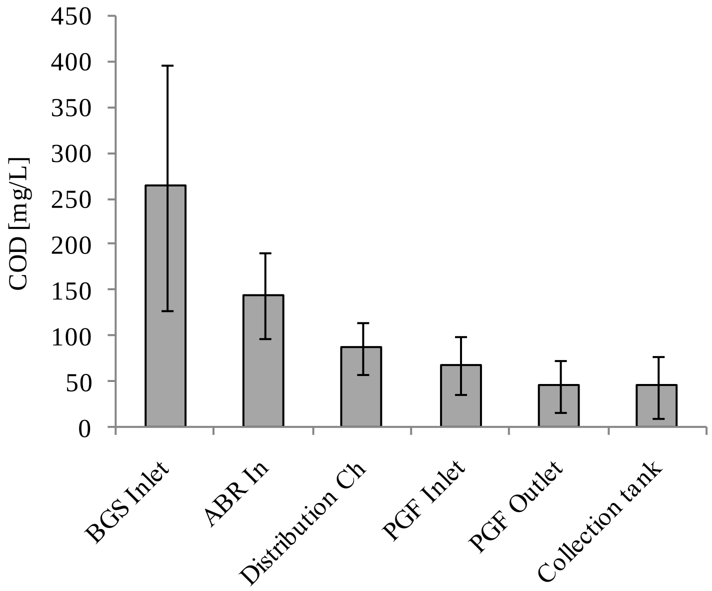

Figure 2. Average COD concentrations and standard deviations for each sampling point at Plant 1.

Plant 1 could have been build much smaller regarding COD concentrations. The average flow was $8.2m^3/d$ in 2010, while the design assumption was $9m^3/d$. Until 2009 the user number was around 60% of the design assumption (40 users compared to the design assumption of 70 users). After 2009 more houses were connected to the plant and the user number went up to 90 persons on most days of the year (ca.129% of design assumption). Due to the increase in user numbers the desludging interval had to be reduced.

Maintenance activities such as desludging and cleaning of the PGF are not reflected in better treatment performance. Increasing concentrations in the collection tank can be attributed to leaf litter and algal growth.

Table 3. Average COD removal efficiencies of the single modules.

	Plant 1 *[%]*	*Plant 2* *[%]*	*Plant 3* *[%]*
Overall	81 (±12)	94 (±5)*	94 (±3)
Settler/BGS	32 (±28)	79 (±14)*	19 (±33)
ABR	54 (±16)	65 (±25)	38 (±27)
AF	-	-	53 (±22)
PGF	34 (±18)	49 (±23)**	73 (±18)
Polishing Unit/Tank	15 (±32)	-	16 (±39)

* values based on high inlet concentrations due to inlet sampling conditions at Plant 2.
** data until May 2008.

Plant 2. Inlet samples are collected from the inlet register to the first treatment module. Here water moves quickly into the BGS while the faeces remain in the inlet register causing high inlet COD concentrations, which are not representative for the total wastewater inflow. COD and BOD show a close correlation. TSS reduction is high through the treatment modules. Phosphorous reduction does not take place. All parameters at all modules show high standard deviations (Table 4).
The Indian discharge standard is generally met after the PGF; for some sampling dates already after the ABR. The pH is almost always above 6.5 enabling anaerobic digestion (Speece, 1996).

Table 4. Average COD, BOD, TSS and Phosphorus concentrations at Plant 2. (CV = Coefficient of Variation)

	COD		BOD		TSS		Phosphorous	
	Average [mg/L]	CV [%]	Average [mg/L]	CV [%]	Average [mg/L]	CV [%]	Average [mg/L]	CV [%]
Settler 1 Inlet	9975* (±12053)	121	3706* (±4267)	115	7523* (±7315)	97	69.2 (±55.5)	80
Settler 2 Inlet	9512* (±9676)	102	4413* (±4969)	113	8264* (±7231)	88	60.9 (±39.4)	65
ABR Inlet	1595 (±1126)	71	801 (±590)	74	2480 (±3871)	156	81.4 (±32.1)	39
ABR 6th Chamber	864 (±764)	88	407 (±362)	89	555 (±992)	179	78.4 (±16.4)	21
PGF Inlet	325** (±229)	70	152** (±107)	70	369** (±559)	152	80.7** (±36.9)	46
PGF Outlet	153** (±55)	36	61** (±22)	36	68** (±58)	85	70.0** (±28.9)	41

* high concentrations due to sampling conditions at the inlet of Plant 2.
** the PGF was only connected until May 2008.

The data does not show a pattern or trend in performance over the entire monitoring period (Figure 3) allowing calculation of means for analysis. Also, for most modules at most sampling dates the variation does not show any pattern. However, from May 2006 to May 2008 inlet and distribution chamber concentrations are much higher in the dry season than in the rainy season. One reason could be water scarcity during the dry season. Due to a lack of flow data this assumption cannot be proven at this point of time.

Figure 4 illustrates the decreasing COD concentration averages of the consecutive treatment modules. Significant decrease of COD concentration means at a 95% confidence interval is found for all treatment steps. However, some dates show an increase of COD concentrations from one sampling point to the next. The ABR shows a removal rate of 65% (Table 3) which corresponds to the design expectations.

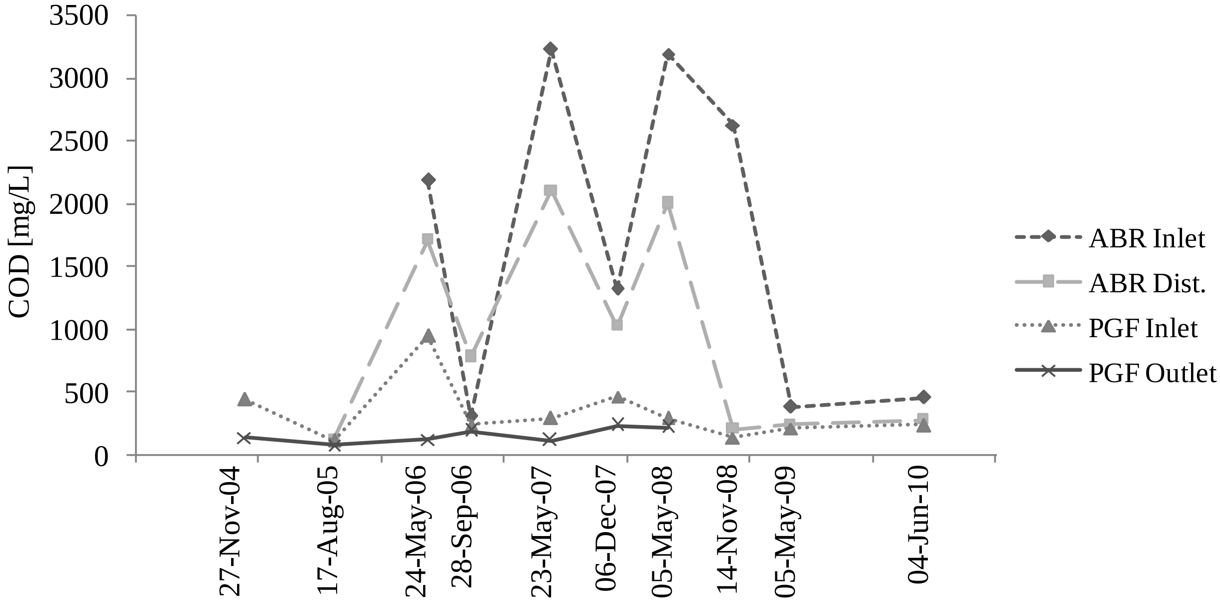

Figure 3. COD concentrations at Plant 2. Each data shows the average from two monitoring rounds. Settler inlet values are excluded due to unrealistically high concentrations. (ABR Dist. = ABR Distribution Chamber)

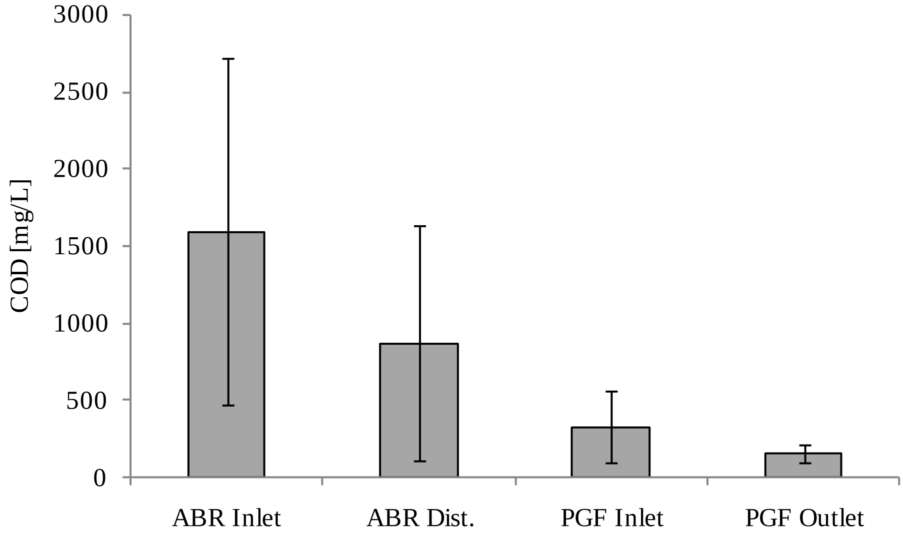

Figure 4. Average COD concentrations and standard deviations for each sampling point at Plant 2.

Regarding COD removal, the design of the plant has suitable dimensions for the amount of wastewater treated. Plant 2 was designed as a community based DEWATS unit, however, with time the user pattern has changed to the one of a public toilet with increased user numbers and predominant usage of urinals. Field observations show reduced water availability in the summer months resulting in lower water usage. This could lead to increased concentrations. Frequent clogging of the inlet chambers and the PGF has been observed. This could be attributed to changes in social dynamics of the community leading to poor O&M practices as well as poor management of the toilets and DEWATS.

Plant 3. The inlet sample is collected from the first chamber of the settler near the inlet pipe which gives more representative samples than the inlet sampling points at Plants 1 and 2. Inlet COD concentrations are comparable to literature values of domestic wastewater (Veenstra *et al.*, 1997). The variation is similarly high for all sampling points (Table 5). The correlation between COD and BOD is high. TSS concentrations show highest reduction at the PGF. Phosphorous concentrations are very low and do not show any removal.

Table 5. Average COD, BOD, TSS and Phosphorus concentrations at Plant 3. (CV = Coefficient of Variation)

	COD		BOD		TSS		Phosphorous	
	Average [mg/L]	CV [%]	Average [mg/L]	CV [%]	Average [mg/L]	CV [%]	Average [mg/L]	CV [%]
Settler 1st Chamber	1730 (±871)	50	1073 (±756)	70	457 (±237)	52	3.5 (±2.6)	74
Settler 3rd Chamber	1650 (±775)	47	887 (±455)	51	506 (±271)	53	4.9 (±2.7)	56
ABR Inlet	2018 (±890)	44	1015 (±364)	36	418 (±207)	50		
ABR - 1st Chamber	2086 (±1077)	52	1008 (±537)	53	725 (±716)	99		
ABR - 4th Chamber	1464 (±888)	61	595 (±286)	48	791 (±952)	120		
Inlet AF (ABR 6^{th})	1244 (±859)	69	606 (±481)	79	634 (±729)	115		
PGF Inlet	477 (±237)	50	224 (±118)	53	322 (±157)	49	5.7 (±3.2)	56
PGF Outlet	109 (±57)	52	39 (±31)	80	86 (±84)	97	4.6 (±2.5)	54
Polishing Unit Outlet	93 (±50)	54	25 (±20)	81	60 (±59)	98	4.0 (±2.5)	64

The Indian discharge standard for COD is generally met at the PGF Outlet; for some sampling points already after the AF. The pH is below 6 up to the AF or PGF for many sampling dates (Figure 5). According to literature (Speece, 1996), no anaerobic digestion should take place in these cases. However, if looking at the COD concentrations for those dates, sometimes the reductions are low as expected, sometimes they are high even in compartments with a low pH. This could be due to the fact that all compartments are heterogeneous, so that even pH varies throughout the compartment. On other sampling dates COD removal is highest at the PGF even if the pH is above 6.2 for all treatment modules.

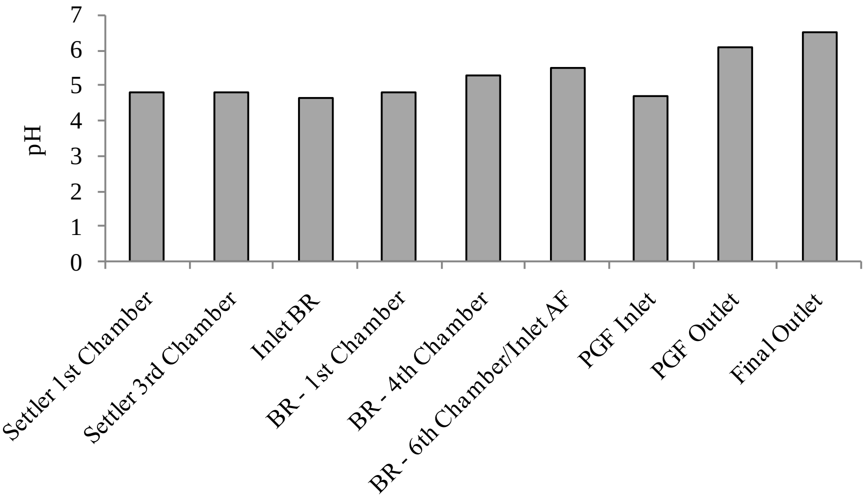

Figure 5. Average pH values at Plant 3.

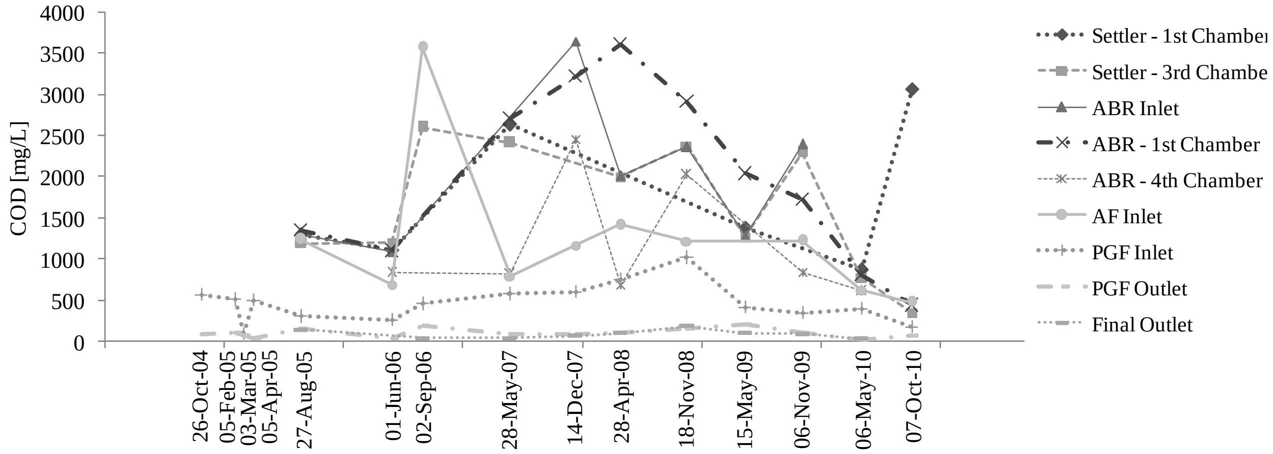

Figure 6. COD concentrations at Plant 3. Each data shows the average from two monitoring rounds.

The data show no pattern or trend in performance over the monitoring period (Figure 6). Therefore, it is acceptable analysing the data using averages. Moreover, no pattern in variation can be observed.

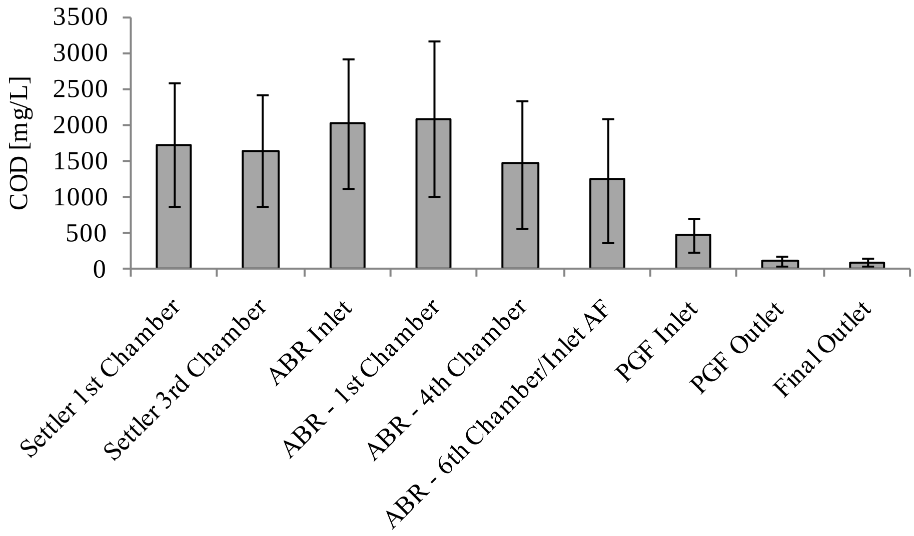

Figure 7. Average COD concentrations and standard deviations for each sampling point at Plant 3.

The average COD concentrations for each sampling point are depicted in Figure 7. Generally, the main reduction at this plant takes place in the AF and PGF. Statistical analysis shows that the settler does not remove COD significantly. In the ABR significant COD reduction takes place up to chamber 4. Significant reduction takes place in the AF and PGF, but not in the polishing unit. The average removal rate of the settler is 19% which is slightly below design expectations (Table 3).

The PGF is flooded most of the time and has very good plant growth. The wastewater is pumped from the AF to the PGF, which results in a very equal distribution of the wastewater in the PGF and might have an effect on the oxygen content of the water. According to the field observation data sheets, rainfall has been recorded on all summer sampling dates though exact precipitation measurements are not available. Rainfall could be a reason showing high removal by the PGF which is due rather to dilution of the wastewater than to treatment processes.
The oil content at the inlet of this plant is very high since part of the wastewater comes from a restaurant kitchen. A grease trap in front of the settler catches the major part of the oil, but the oil content remains high even after the grease trap. The high oil content could be a reason for the relatively low performance of Settler and ABR as large amounts of oil can lead to high concentrations of fatty acids which inhibit the methanogens due to high hydrogen partial pressure. This restricts the degradation of COD until the boundary conditions change. However, the data indicate that some removal happens even when the pH is low.

CONCLUSIONS AND RECOMMENDATIONS

Objective 1: Assessment of long-term monitoring data regarding performance

The data-set analysed in this study shows high variation in COD concentrations and removal efficiencies at all plants. Reasons for variation in the data can be (i) unrepresentative sampling, (ii) errors in analytical methods or (iii) actual variation of the wastewater characteristics due to differing organic or hydraulic loading as well as changes in the plant's performance. Calculations show that the measured values at the inlet of Plant 1 represent only 26% of the calculated feed concentration values based on a onetime flow measurement and user count. This could indicate unrepresentative sampling. The high variation cannot be fully explained from existing information. Due to the high variation and possibly unrepresentative sampling the calculated removal rates should be treated with caution and definite conclusions cannot be drawn. However, general trends can be established. Statistical analysis indicates significant reduction of COD concentrations for most treatment steps. The COD discharge standard in India of 250 mg/L is met at all monitoring dates.

The treatment performance of the plants does not show a constant increase or decrease of treatment capacity over the years. This could imply that the plants have not reached their critical performance level. That is, the effluent concentrations are within the standard discharge limits in India. This can mainly be attributed to regular desludging based on field observations (e.g., low biogas production and high sludge levels) before a critical performance is reached. Possibly, critical performance could have been reached at some point of time between monitoring dates, however not being reflected in the data if O&M activities were performed before the next monitoring date. Thus, the large time gap between monitoring dates does not allow a definite conclusion about reaching critical performance.

Changes in the plants performance can be influenced amongst others by the following factors:

- variation in usage of the sanitation facilities: fluctuation of organic and hydraulic loading
- variation in amount of water used (e.g., due to water scarcity): fluctuation of hydraulic loading rates
- acceptance by the community: physical condition of the plant (e.g., depositing of trash on the plant or stealing of lids)
- regular maintenance and clear maintenance responsibilities: physical condition of the plant (e.g., desludging of treatment modules, cleaning of filter material and quick removal of clogging in pipes)

- variation of oil and grease removal frequency (relevant for plant 3)
- variation in chemical usage for cleaning (e.g., phenyl, detergents)
- precipitation pattern

As a conclusion, further research should be conducted on how to improve representative sampling, especially regarding feed samples. Attribution of the variation in monitoring data to single influencing factors is desirable in order to improve data analysis. Regarding the performance of Plant 3, more detailed investigations should be considered in order to understand why treatment takes place despite the high oil and grease content and low pH of the wastewater.

Objective 2: Improvement of wastewater monitoring

Experience has shown that wastewater monitoring is subject to a number of practical limitations. This is mainly because of the plant's size, its operating conditions, location and analytical capacity of laboratories and its location in a developing country:

i. Logistic issues
    - high number of DEWATS units at different locations: logistics, transportation
    - remote locations: logistics, transportation and the intermittent availability of electric power
    - lack of a sufficient number of trained staff (or lack of funding for trained staff)
    - limitations in flow measurements
    - no laboratories available on or near site
    - analytical uncertainties due to varying degrees of quality standards in most commercial laboratories
    - lack of advanced monitoring equipment
    - stealing of expensive material (e.g., flow meter)

ii. Financial issues
    - limited funding (NGOs, communities)
    - expensive laboratory analysis

iii. Data analysis and interpretation
    - incomplete documentation of facilities
    - incomplete knowledge about history of the plant (e.g., additional connections and O&M activities)
    - monitoring performed by several people due to the long monitoring history

These observed practical limitations should be considered while formulating recommendations for improved wastewater monitoring of DEWATS.

Practical experience shows that the main problems regarding functioning of the plants are due to insufficient O&M activities, e.g., clogged pipes are not cleared quickly. As supported by the findings of a study by Environment and Public Health Organization (unpublished), responsibilities must be clear and staff with knowledge on O&M must be available for each site. For this paper a record of all O&M activities at the plant, infrastructure changes and assessment of user numbers was compiled in order to interpret monitoring results. It is advisable to keep an updated record of all monitored plants at all times so that all events are documented. It has to be elaborated whether the record should be the responsibility of the operator or the monitoring agency (e.g., CDD Society). Operators could face problems with the implementation of this record as they generally might not have staff with the required background. Therefore, record keeping could be considered part of the monitoring and be performed by the monitoring agency. However, it is difficult to keep track of all activities at the plant in between monitoring dates.

Practical observations of the social environment at the three plants indicate that a steady and controlled environment shows a more steady performance. In Plant 1 lower performance variations are observed which could be attributed partially to the almost constant number of users, high responsibility of the users and regular O&M practices indicate whereas in Plant 2 and 3 the variable social environment results in higher performance variations. Experience has shown that there are fewer incidents of malfunction such as clogging of pipes and PGF at Plant 1. These findings indicate that performance evaluation of a full-scale DEWATS under real conditions cannot be limited to a purely technical monitoring of each module as each plant is highly influenced by their social and environmental surroundings. This leads to the conclusion that those factors must be incorporated in the data collection in order to better understand variations in technical performance of the plant.

Taking these observations into consideration, additional parameters for monitoring could include amongst others:

(a) Number of users, type and their behaviour
(b) Continuous record of all O&M activities and changes to the plant
(c) O&M responsibilities
(d) Precipitation data (patterns and quantity)
(e) Robust methods of flow measurement (bucket method)
(f) Sludge height measurements (if practical)

Including these factors in the monitoring programme could be a step towards a better understanding of variation in the data.

Limitations of DEWATS monitoring explained above do not allow a resource intensive monitoring programme (e.g., 24h composite sampling). A more frequent monitoring than the one performed in this study (once every 6 months at inlet and outlet of each module) would be desirable, but is not realistic due to financial and time constraints. However, if practical conditions allow, in-depth monitoring of single plants with an increased number of sampling points and rounds over a concentrated period of time would be helpful to understand treatment performance.

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