PERFORMANCE BENCHMARKS FOR MUNICIPAL WASTEWATER TREATMENT PLANTS

A guide for practitioners

ENERGY EFFICIENCY
RETROFIT STRATEGIES

TREATMENT EFFICIENCY
SLUDGE PRODUCTION

GHG ESTIMATION
AREA REQUIREMENT

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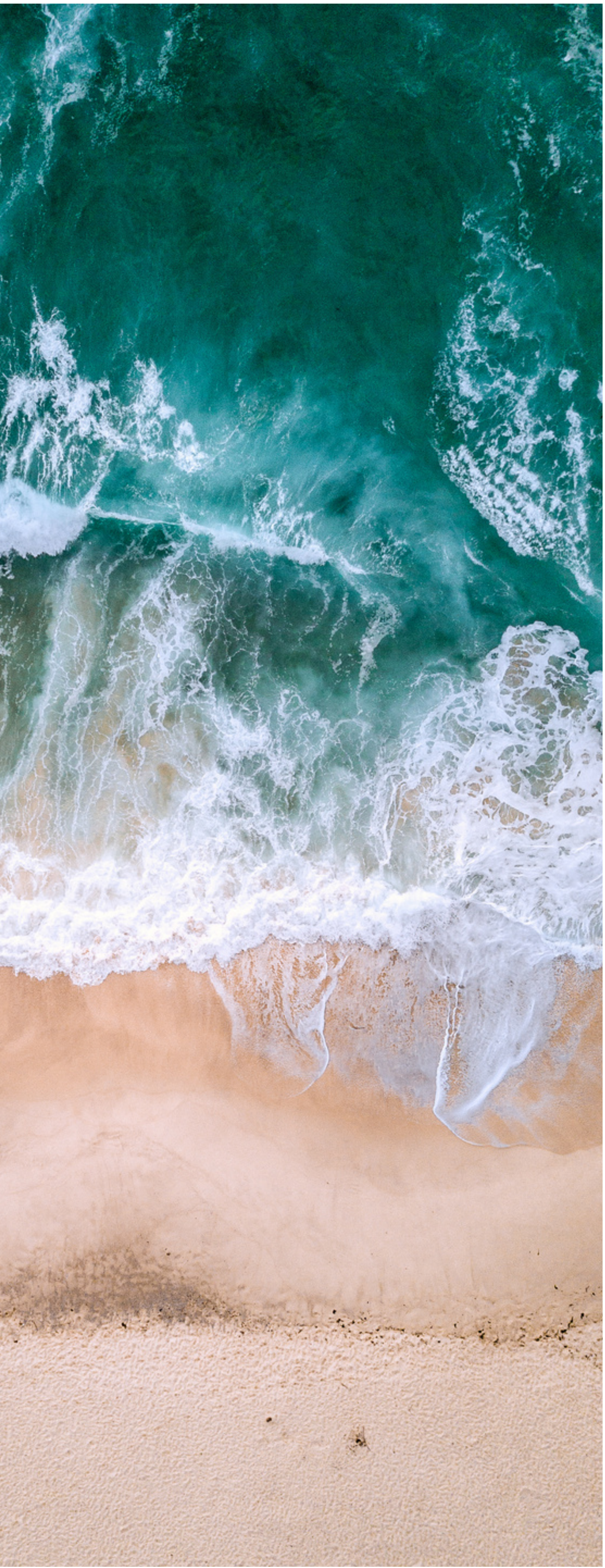

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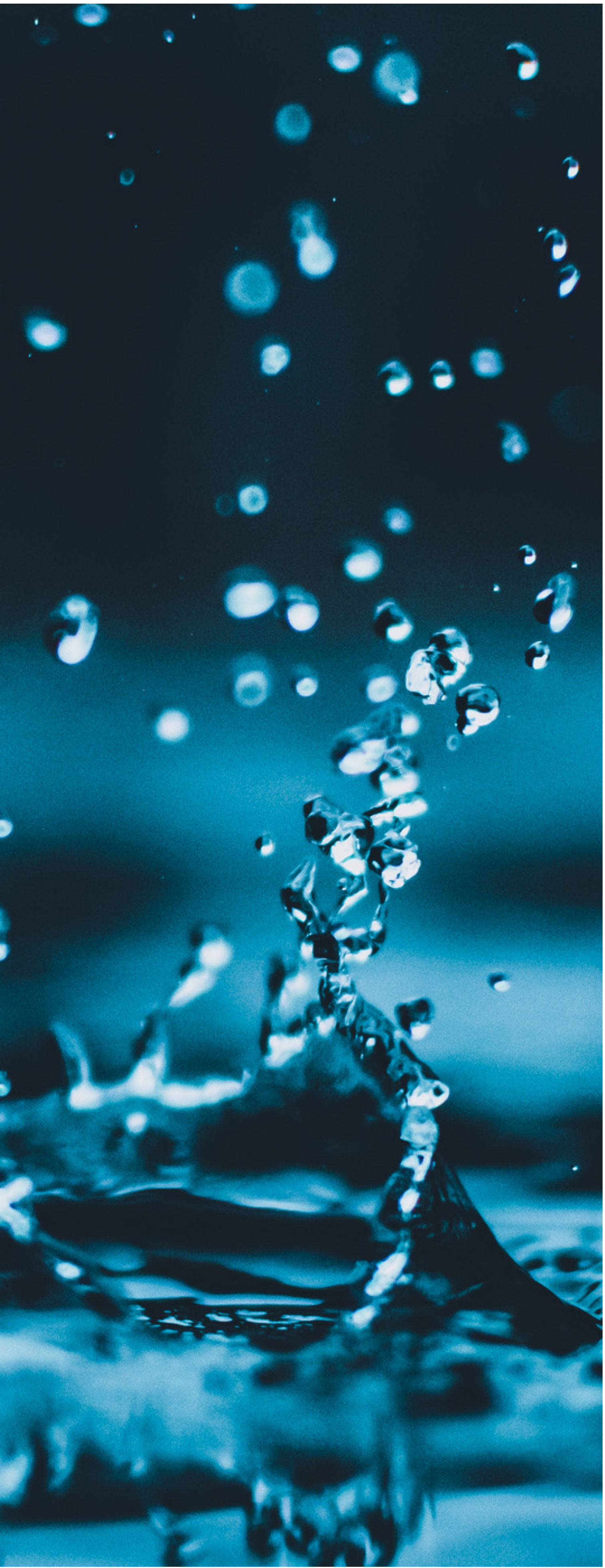

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LIST OF ABBREVIATIONS

AD	Anaerobic digestion
ASP	Activated sludge process
BNR	Biological nutrient removal
CAS	Conventional activated sludge
COD	Chemical oxygen demand
DO	Dissolved oxygen
EA	Extended aeration
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
KPI	Key performance indicator
MBBR	Moving-batch biological reactor
MBR	Membrane bioreactor
MCF	Methane conversion factor
PE	Person equivalent
SBR	Sequential batch reactor
SNH	Ammoniacal nitrogen
SRT	Substrate retention time
SS	Suspended solids
STP	Sewage treatment plant
TN	Total nitrogen
UASB	Up flow anaerobic sludge blanket
VFD	Variable frequency drive
VOC	Volatile organic compounds
WSP	Waste stabilization ponds

1. Introduction

Optimization of sewage treatment plants (STPs) improves pollution removal efficiencies, reduces operation and maintenance costs, GHG emissions and helps comply with changing environmental norms. STPs account for about 3% of the methane emissions and their optimization could have a significant impact in limiting global warming increase by 2 degree celsius (Magill, 2016).

The objective of this study is to evaluate performance indicators and emission criteria for municipal STPs. The study focusses on the following:

- Identification of key performance indicators (KPIs) that can be used for evaluating new STPs.
- Identification of process and infrastructure retrofits for existing STPs.
- Criteria for calculating GHG emissions for STPs.

2. Key Performance Indicators for STPs

Traditionally, energy benchmarking for STPs are related to the energy consumption and its relation to the volume of treated water (Kwh/m3). This approach is simple and easy to implement; however, it assumes that pollutant concentrations in the influent and effluent do not vary significantly in the STPs. This assumption is not valid, especially when the collection systems, treatment technologies and the population served have different characteristics. Additionally, Kwh/m3 just relates the energy consumption to the amount of water passing through the treatment plant, without evaluating the efficiencies of the treatment plants to remove pollutants. Kwh/m3 is highly influenced by the dilution factor of the wastewater.

An alternate approach is to measure the energy consumption in relation to the amount of pollutants removed; for example, KWh/KgCODremoved or KWh/KgTNremoved. The main disadvantage of this approach is that the measurement of pollutant removal is more complicated than flow measurement, and therefore, it is less feasible.

Generally, large STPs are more energy efficient compared to the small-scale plants. This is due to: (i) Economies of scale: Due to the usage of larger and more efficient equipment, and (ii) Process stability: This is reflected by a regular operation of electromechanical equipment and thus avoiding energy-intensive transitional periods (Longo, et al., 2016).

The following table summarizes energy KPIs for various municipal-scale STP technologies:

Table 1: Energy related KPIs for STP operations (ENERWATER, 2020) (Haas, Appleby, Charakos, & Dinesh, 2018) (Longo, et al., 2016) (NGRBA, 2010)

#	Technology	Average kWh/Kg COD removed	Average kWh/m3
1	CAS	0.98	0.54
2	MBBR	0.35	0.22
3	SBR	1.28	0.21
4	UASB	0.21	0.13
5	EA	2.25	1.46
6	MBR	2.80	1.11
7	WSP	1.20	0.48
8	BNR	1.13	0.66

The pollutant removal efficiency of the above technologies varies based on operations and design criteria. However, a subject ranking of the technologies (1=Poor and 4= Excellent) is shown in the following table along with Eutrophication potential which reflects the efficiency of the removal of COD, nitrogen (N) and phosphorus (P) and represents the emission of the remnants in the water discharge:

Table 2: Subjective ranking of pollution removal (Sun, et al., 2020)

#	Technology	COD Removal	N Removal	P Removal
1	CAS	3	2	2
2	MBBR	3	2	2
3	SBR	3	3	3
4	UASB	3	1	1
5	EA	3	2	2
6	MBR	4	2	2
7	WSP	2	2	2
8	BNR	3	4	4

Note: 1=Poor and 4= Excellent;

The KPIs for sludge production, CAPEX and OPEX and land requirements deduced from various studies and projects are shown in the following table:

Table 3: Specific sludge production (Andreoli, Sperling, & Fernandes), investment and operational costs (NGRBA, 2010) and land requirement (NGRBA, 2010) and (Kalbar, Karmakar, & Asolekar, 2012)

#	Technology	Sludge Production kg SS/kg COD	CAPEX $/m3.d	OPEX $/m3	Area m2/m3.d
1	CAS	0.70	142	0.14	1.20
2	MBBR	0.40	142	0.15	0.55
3	SBR	0.70	151	0.11	0.45
4	UASB	0.26	142	0.14	1.11
5	EA	0.53	151	0.14	1.3
6	MBR	0.50	395	0.26	0.45
7	WSP	0.45	83	0.11	6.10
8	BNR	0.70	151	0.14	1.3

Note 1: Sludge Production –SBR and BNR are assumed to have similar production rates as CAS and MBR and MBBR have lower rates than CAS.

Note 2: CAPEX and OPEX – EA and BNR are assumed to have similar costs as compared to CAS. These are reference values for India based on conversion factor of 1 USD ($)= 75 INR and the costs will vary for each country.

3. Optimization and retrofit of existing municipal STPs

The parameters and criteria for optimization and retrofit of existing municipal STPs depend on the type of technology, capacity, design criteria, operations and maintenance efficiencies, costs, etc. The process improvement, especially, need to be verified with the design data before implementing changes. A brief description possible process, equipment and infrastructure related optimizations and retrofits are shown in the table below:

Table 4: Optimization and retrofit interventions in STPs (El-Sheik, 2011) (Guo, Sun, Pan, & Chiang, 2019) (Revollar, Vilanova, Vega, Francisco, & Meneses, 2020) (US EPA, 2015) (Kato, Fujimoto, & Yamashin, 2019) (EPA, 2010) (Maktabifard, Zaborowska, & Makinia, 2018) (IBM, 2016) (Grobelak, Czerwínska, & Murtas, 2019) (Etienne & Spérandio, 2001)

#	Intervention	Type of intervention	Results in	Potential benefits
1	Renewable energy (Solar, wind, biogas, etc.)	Energy source	Reduced costs and GHG emissions	Energy sufficiency
2	Improved primary treatment (Eg: fine screens and primary sedimentation tanks)	Equipment	Improves SS and BOD removal, reduces risk of clogging and damage to mechanical equipment	At least 15% reduction in energy costs of the STP due to reduced BOD
3	Efficient pumps and VFD for internal sludge recycling	Equipment	Reduced energy requirement and long life of pumps	At least 10% reduction in energy consumption
4	Retrofit of efficient blowers and diffusers (eg: fine bubble diffusers)	Equipment	Reduced energy requirement and improved life span	Between 10 - 30% reduction in total energy costs
5	VFD to control aeration equipment using DO control and optimization	Equipment	Reduced energy requirement and improved oxygen transfer	Between 10 - 30% reduction in total energy costs
6	Air pressure control in blowers	Equipment	Better aeration control and avoids surge	Between 10 - 30% reduction in total energy costs

#	Intervention	Type of intervention	Results in	Potential benefits
7	Sludge disposal - Biogas	Infrastructure	Production of methane, heat and electricity	Between 20 - 40% energy efficiency due to use of biogas
8	Sludge disposal - composting	Infrastructure	Production of low-quality compost	Requires co-composting to balance C:N. This can be used as a soil conditioner.
9	Sludge disposal - Solar Greenhouse drying	Infrastructure	Sludge volume reduction and production of high calorific value granules	> 70% reduction in sludge disposal cost due to volume reduction
10	Sludge disposal - Thermal drying	Infrastructure	Sludge volume reduction	> 70% reduction in sludge disposal cost due to volume reduction
11	Optimization of SRT, MLSS, F/M, recycle/return rate, etc.	Process	Efficient operations	Optimization of MLSS results in up to 10% reduction in treatment costs
12	Monitoring of ammonium conc. in the effluent and aeration control	Process	Optimization of aeration	Cost savings are linked to aeration and recirculation pumps.
13	Monitoring of nitrites in anoxic tank	Process	Optimization of internal recirculation	Cost savings are linked to aeration and recirculation pumps.
14	Optimization of Food to Mass ratio	Process	Efficiency and reduced energy requirement for recirculation pumps and aeration	Cost savings are linked to aeration and recirculation pumps.

#	Intervention	Type of intervention	Results in	Potential benefits
15	Online monitoring and IoT	Process	Efficient operations	Aprox. 15% reduction in energy costs, 14% reduction in chemicals (in case of P removal implemented) and 17% reduction in sludge production
16	Implementation of chemical phosphorous removal	Process	Increases phosphorous removal efficiency	Up to 7 times higher cost compared to biological Phosphorous removal
17	Stabilization of alkalinity for nitrogen removal	Process	Increases chemical costs but decreases energy costs and improves efficiency	-
18	Implementation of biological phosphorous removal	Infrastructure and process	Increases pollution removal efficiency	-
19	Implementation of nitrogen removal	Infrastructure and process	Increases pollution removal efficiency, reduces aeration requirement and reduces sludge production	Over 30% reduction in energy requirements
21	Pressure monitoring, backwash control for membranes	Instrumentation	Efficient operations and increase in the life of membranes	Between 35 - 40% of energy consumption reduction

Note: The values and recommendations mentioned in the above table are based on authors' experience with STPs and references from various studies globally. However, the results may vary for each project and should be applied with expert opinion.

4.Low-cost municipal wastewater treatment

Globally, about 30 million hectares of land are affected by untreated wastewater and about 65 % of irrigated croplands in several developing countries are located within 40 km of urban areas with high levels of wastewater dependencies. About 885 million people in such countries are exposed to high health and environmental risks (UN Environment, 2017). In several small towns (< 10.000 P.E.) and cities, implementing a conventional STP might not be feasible due to budget constraints for investment or operational costs. Decentralization and implementation of low-cost or natural treatment systems can help in balancing the trade-offs between environmental and economic objectives.

In many small towns, stormwater and wastewater are often combined in the sewer system and hence including detention tanks to ensure only the base flow is treated is recommended. Wastewater treatment occurs in primary, secondary, tertiary and advanced treatment steps depending on the technology. Primary treatment alone with sedimentation can remove approximately 25 – 50 % of the BOD, 50 – 70 % of SS and about 65 % of oil and greases (FAO, n.d.).

Some low-costs treatment systems such as the following can be applied to de-centralized or small towns:

Wastewater stabilization ponds (WSP) or lagoons
- Anaerobic lagoons
- Facultative lagoons
- Aerated ponds
- Combination of the above

Constructed wetlands
- Horizontal sub-surface wetlands
- Vertical sub-surface wetlands
- Free water wetlands

5.GHG emissions from wastewater treatment

Wastewater contains various organic and inorganic pollutants that are transformed into gaseous and physical states during treatment processes. Untreated sewage on the other hand can result in direct methane emissions depending on its discharge to lakes, rivers, sea or stagnant water and sewers. The operations of wastewater treatment plants can result in both direct and indirect emissions.

5.1 Untreated sewage

Emissions from untreated sewage depends on the concentration of organic pollutants and type of discharge. The main GHG emissions are likely to be CH_4 and N_2O due to anaerobic conditions and nitrification-denitrification reactions. IPCC has devised methane conversion factors (MCFs) for estimation of emissions from untreated sewage (IPCC, 2006). Based on the MCFs and maximum CH_4 producing capacity for domestic wastewater, the following emissions are calculated:

Table 5: Emissions from untreated sewage (IPCC, 2006)

#	GHG	Source	Value	Unit	Discharge
1	CH_4	Raw sewage	0.025	kg CH_4/ kg COD	sea, river and lake
2	CH_4		0.125		Stagnant sewer

5.2 Treated sewage

The emissions from treatment of wastewater depends on the efficiency of operations and pollutant removal. The STP operations can result in direct and indirect emissions.

5.2.1 Direct emissions

The direct emissions occur because of biological degradation reactions (Campos, et al., 2016). The main GHG emissions are CO_2, CH_4 and N_2O.

- The CO_2 emissions are due to the biological degradation of organic BOD and COD and this is not considered for emission calculations as they origin from biogenic sources (IPCC, n.d.). However, improper operations such as longer substrate retention times (SRT) can lead to higher emissions of CO_2.

- The CH_4 emissions might occur due to poor aeration and mixing in the biological reaction tanks, sludge storage tanks, thickeners, etc. The CH_4 emissions from sludge disposal are considered as indirect emissions and are described later in this report.
- The N_2O emissions result from the nitrogen removal processes in the wastewater treatment plants. This is a trade-off between emissions and nutrient removal as removal process results in the highly potent GHG emission of N_2O but avoiding this process will result in eutrophication and pollution to the downstream waterbodies and soil.

The calculations of direct emissions for CO_2, CH_4 and N_2O based on the pollutant loads or the pollutant removal efficiencies are described below:

Table 6: Direct emissions from treatment of sewage (Campos, et al., 2016) (Yan, Li, & Liu, 2014) (Piao, Kim, Kim, Kim, & Kim, 2016)

#	Type	Source	Value	Unit	Remarks
1	CO_2 biogenic	Biological degradation	0.08	kg CO_2/ kg COD removed	Not counted according to IPCC recommendation due to its biogenic source.
2	N_2O	Nitrogen removal	0.0016	kg N_2O/ kg TN removed	This is according to total nitrogen removed in the treatment plant
3	N_2O		0.0042 0.0365	kg N_2O/ kg TN	This is according to total nitrogen load. (i) CAS+ AD for sludge treatment (ii) BNR + Sludge treatment
4	CH_4	Sludge thickeners and storage tanks, biological treatment	0.0012	kg CH_4/kg COD removed	This is according to total nitrogen removed in the treatment plant
5	CH_4		0.0046 0.0389	kg CH_4/kg BOD	(i) CAS+ AD for sludge treatment (ii) BNR + Sludge treatment

5.2.2 Indirect emissions

The indirect emissions can result due to the following:

- Energy consumption of STP operations: The CO_2 emissions depends on the consumption of electricity or heat (in cold climates for AD operations) and the corresponding emission factors. This depends on the source of energy (eg: thermal, hydroelectricity, renewable energy, etc.).

- **Sludge treatment and disposal: This depends on the disposal pathways for sludge such as direct land application, composting, AD, incineration of dried sludge, etc.**

The total emissions from an STP is the sum of its direct and indirect emissions as described in the following equations:

Total Emissions = Total direct emissions + Total indirect Emissions

Total direct emissions = CO_2 emissions (depending on COD or BOD degradation)
+ N_2O emissions (depending on nitrogen removal)
+ CH_4 emissions (depending on COD or BOD degradation)

Total indirect emissions = Emissions from energy usage for operations
+ Emissions from sludge treatment and disposal

Emissions from sludge treatment = Emissions from input energy for process
- Offsets due to generation of electricity and heat recovery
+ Emissions related to the process

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