Development of Cost Functions for Biological Treatment by Membrane Bio-Reactor

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Graphical abstract

Abstract

One of the space-saving and alternative options for wastewater treatment is the use of Membrane Bio-Reactor. This paper delineates the sequential approach to explore integrated cost functions for estimation of the forecast level cost for biological treatment of wastewater by use of Membrane Bio-Reactor. The cost functions for capacity wise small range, medium range and large range groups of wastewater treatment plants with Membrane Bio-Reactor have been developed based on process design and cost estimation. It has been established through regression analysis that they are best expressed by polynomial equations. Validation of cost functions has been executed by assessment of mean absolute percentage errors. The respective determination coefficients in respect of cost functions for capacity wise small range, medium range and large range are 1, 0.9995 and 0.9996. The respective mean absolute percentage errors with reference to the cost functions for capacity wise three different ranges are 0.18 %, 0.82 % and 0.63 %. In each case the value of mean absolute percentage error is well below 10 %. This study has established that accurate forecast level cost may be arrived by integrated cost functions developed for capacity wise three different groups of wastewater treatment plants with Membrane Bio-Reactor.

Keywords: Determination Coefficient, Mean Absolute Percentage Error, Regression Analysis, Cost Function

1. Introduction

1.1. BACKGROUND OF THE STUDY

Growth of industries across the developing countries has raised the need of water supply at significant level. The quality of such water supply is also a concern to promote the growth of industries. On the other side, enormous growth of population has resulted huge amount of wastewater discharge into the environment. In most of the countries, river is the source of major water supply and in many cases community wastewaters without any treatment are discharged into it. Several initiatives are adopted at government level to protect the quality of river water source by installation of wastewater treatment plant (WWTP). In India, Namami Ganga Projects are under implementation phase to prevent the river pollution through construction of new WWTPs.

Treatment of wastewater by use of Membrane Bio-Reactor (MBR) produces high quality of treated water. Therefore MBR may be considered as an effective option to cater the requirement of water supply for industries as addressed above. MBR technology is an integrated hook-up of activated sludge process (ASP) and membrane filtration. It does not call for the requirements of primary clarifier and secondary clarifier as envisaged for conventional ASP. Thus use of this MBR technology reduces the requirement of space for installation of WWTP. It has wide application for municipal and industrial wastewater treatment. Technologies like moving bed biofilm reactor

(MBBR) and sequential batch reactor (SBR) also require lesser footprints compared to ASP and produce quality treated wastewater (Manual on Sewerage and Sewage Treatment Systems published by CPHEEO in collaboration with JICA).

It is a fact that large vacant piece of land required for construction of WWTPs based on conventional technologies is now seldom available in dense urban area. This constraint may be more or less managed by constructions of WWTPs with space-saving technologies. The task of selection of most suited and economic option among space-saving MBR, MBBR & SBR technologies in respect of wastewater treatment at a particular site is truly a challenging exercise. Therefore, a suitable approach that would determine or estimate the rapid forecast level cost with adequate accuracy for WWTP with each of the above technologies appears to be very much necessary and beneficial.

1.2. SHORT REVIEW OF THE PERTINENT LITERATURE

Literature review in reference to the subject investigation work reveals that a number of earlier studies have been undertaken since last fifty years in connection with cost functions for construction as well as operation of WWTPs (Acampa *et al*., 2019; Arif *et al.*, 2020; Balmer and Mattson, 1994; Doherty, 2017; Gillot *et al*., 1999; Gratziou *et al*., 2006; Jafarinejad, 2016; Koul and John, 2015; McNamara, 2018; Nogueira *et al*., 2007; Papadopoulos *et al*., 2007; Qasim *et al*., 1992; Sekandari, 2019; Shah and Reid, 1970; Singhirunnusorn and Stenstrom, 2010; Yengejeh *et al*., 2014). A cost function is an expression used to predict how expenses will change at different input levels to a system. There are miscellaneous methods which have been addressed to develop cost functions for forecasting costs of WWTPs. Gratziou *et al*. (2006) compared the total costs for several small scale sewage treatment systems. They calculated costs for construction and operation based on functions for cost elements available in literature. By use of CapdetWorks, Jafarinejad (2016) estimated the costs for conventional activated sludge, extended aeration activated sludge and sequencing batch reactor systems in Tehran - Iran for a comparative analysis. Koul and John (2015) presented Life Cycle Cost Analysis for Up-flow Anaerobic Sludge Blanket Reactor, SBR and MBBR based on available information from different existing WWTPs. Papadopoulos *et al*. (2007) collected data for land requirement, costs of construction, operation and maintenance of existing wastewater treatment facilities. They developed twelve equations applying ordinary least squares and fuzzy linear regression techniques. Shah and Reid (1970) developed cost functions for WWTP based on feedback survey over 563 plants located in 48 states in USA. Based on cost data collected from a number of municipal WWTPs, Singhirunnusorn and Stenstrom (2010) proposed cost functions to assess activated sludge, oxidation ditches, aerated lagoons and waste stabilization ponds to assess costs for land, construction, operation and maintenance in Thailand.

From the review of various published literatures it is observed that in most of the cases the cost functions for construction, operation and maintenance of WWTPs as reported are on the basis of country or location specific historic cost data (recorded, published & available data) for conventional technologies (Koul and John, 2015; Papadopoulos *et al*., 2007; Shah and Reid, 1970; Singhirunnusorn and Stenstrom, 2010; Yengejeh *et al*., 2014). Some of the investigators (Arif *et al.*, 2020; Jafarinejad, 2016) used CapdetWorks software for selection of conventional technologies with respect to specific inflow rate of wastewater. However a rational approach for development of cost functions based on technology specific engineering design and cost estimation over a capacity range has not been noted in the literatures. Few numbers of additional studies with reference to cost functions for space-saving MBBR & SBR technologies as low foot print systems are presented in the literatures (Jafarinejad, 2016; Koul and John, 2015).

1.3. ORIGINALITY OR NOVELTY OF THE RESEARCH

With due consideration of the gap as noticed from literature review and aiming to present a rational base, a novel research initiative is required to develop a tool for basic engineering and forecasting cost by means of cost functions on the basis of realistic estimation in detail for space-saving technologies based WWTPs without applying any historic cost. It appears to be very much meaningful, rational and useful in respect of location across any country for practical purpose especially for decision making process by the vendors and owner of plants. Space-saving technologies have been given due importance in respect of usual space constraints in urban areas. One of the space-saving technologies available, MBR has been focused in the present paper as MBR technology in many cases has been referred as preferential wastewater treatment technology over ASP - the conventional technology used over a long period of time. MBR is regarded as an important innovation since it does not require secondary clarifier and therefore can eliminate the necessity of a large space. MBRs are suitable for use in both municipal as well as industrial wastewater treatment which is an integrated system comprised of conventional biological treatment system and membrane filtration – known as hybrid bioreactor. Use of MBR technology enables to achieve advantages over ASP as follows:

- Superior quality of treated effluent
- Higher volumetric loading rates
- Reduced hydraulic retention times
- Extended solid retention times
- Nitrification and Denitrification due to higher solid retention times and high bacterial removal efficiency.

Use of membrane filtration eliminates the need for secondary clarifiers and thus reduces the requirement of plant area in a significant manner. However, the MBR technology encompasses few limitations like higher energy consumption vis-à-vis cost, membrane fouling problems and high maintenance costs for periodic replacement of membranes. A set of cost functions for BOD removal in MBR over wide range of capacity for estimation of capital cost and cost of energy requirement, operation as well as maintenance over 25 years have been derived by application of regression techniques in the present paper. The derived cost functions are believed to be very useful henceforth for comparative assessment of technologies available for construction of new WWTPs.

1.4. RESEARCH OBJECTIVES

In general wastewater is treated in successive stages such as primary, secondary and treatment of biological sludge for safe disposal into the environment. Methods of treatment of wastewater in grit chambers and that of biological sludge are relatively same in most of the cases and the domain of alternatives for such treatment is very restricted. Therefore the cost of such treatment for a specific input rate of wastewater and biological load will remain more or less same for each of space saving technologies under concern. However cost of biological treatment will depend upon the kind of the bio-reactor technology chosen for obtaining desired results in respect of safe discharge in the outfall. Thus it may be prudent to conclude that the comparison among the costs of bio-reactors along with pre-treatment and post-treatment facilities as necessary will enable to select the most suitable technology for a specific case. The approach for development of a tool in respect of rapid estimation for life cycle cost of biological treatment in a WWTP with MBR technology has been delineated hereinafter.

2. Materials and methods

2.1 CAPACITY GROUPS

Economy of scale is applicable in case of WWTP. In general, unit cost of WWTP decreases with increase in capacity. It is not appropriate to envisage a single cost function over a wide range of capacity range. WWTPs have been categorised capacity wise in multiple groups viz. small (0.5 – 5.0 MLD), medium (5.0 – 50.0 MLD) and large (50.0 – 150.0 MLD).

2.2 DESIGN INPUT QUALITY OF WASTEWATER

The characteristics of raw wastewater depend on rate of water supply and pollution load per capita. The design concentrations of impurities in raw wastewater based on water supply @ 135 lit / cap / day are exhibited in Table 1 (Manual on Sewerage and Sewage Treatment Systems published by CPHEEO in collaboration with JICA).

Table 1. Design input quality of Wastewater at inlet to WWTP

Parameters	**Value**	**Unit**
Biological oxygen demand (**BOD**)	250.00	g / m^3
Chemical oxygen demand (**COD**)	425.00	g / m^3

Volatile suspended solids (**VSS**)	262.50	g / m^3
Total suspended solids (**TSS**)	375.00	g / m^3
Ammonia Nitrogen (**NH_4-N**)	32.50	g / m^3
Organic nitrogen (**ON**)	17.50	g / m^3
Nitrate Nitrogen (**NO_3-N**)	5.00	g / m^3
Total kjeldahl nitrogen (**TKN**)	50.00	g / m^3
Total phosphorous (**TP**)	7.10	g / m^3

2.3 DESIGN TREATED QUALITY OF WASTEWATER

The stipulations established by the Ministry of Environment & Forests (MoEF) of the Government of India (GOI) have been considered as the treated water quality. These are enlisted hereinafter for ready reference:

Table 2. Design treated wastewater quality

Parameters	**Value**	**Unit**
Biological oxygen demand (**BOD**) - design limit	10.00	g / m^3
Total suspended solids (**TSS**)	10.00	g / m^3

2.4 TREATMENT PROCESS CONSIDERED

MBR technology comprises of activated sludge process and membrane separation process. In general low pressure membranes are used. Membranes are kept submerged in the reactor itself or otherwise in a separate chamber to promote separation of solids from the liquid. Primary sedimentation tank, final sedimentation tank and disinfection facilities are not required to be installed in this process. A schematic for MBR Process Cycle is reproduced below:

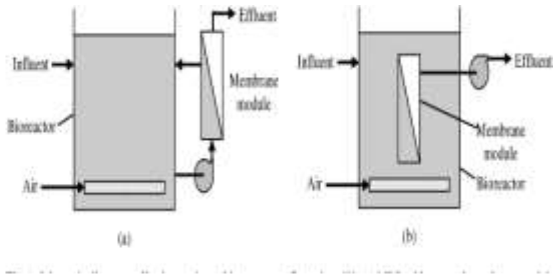

Figure 1. MBR Process Cycle

A typical arrangement for membranes is furnished below:

Figure 2. View of MBR Membranes

2.5 DESIGN PARAMETERS FOR MBBR

The design parameters as envisaged for biological treatment in MBR based WWTPs are tabulated hereinafter as shown in Table 3 (Metcalf & Eddy Inc, Wastewater Engineering, Treatment and Reuse, Fourth Edition, McGraw Hill):

Table 3. Design parameters as adopted for biological treatment in WWTPs

Parameters	Value	Unit
Peak factor	2.25	
Lean Factor	0.45	

Table 3. Design parameters as adopted for biological treatment in WWTPs (continued)

Parameters	Value	Unit
Thickener overflow return as fraction of plant flow	0.15	
BOD in thickener overflow return	500.00	g / m^3
Centrate from sludge dewatering as fraction of	0.0060	

plant flow		
BOD in centrate from sludge dewatering return	380.00	g / m^3
BOD_u/VSS	1.42	g BOD / g VSS
BOD_5 / BOD_u	0.67	
Kinetic parameters for BOD removal		
Reference temperature for kinetic parameters	20.00	deg C
Half Velocity Constant	20.00	g bs COD / m^3
Maximum specific bacterial growth rate	6.00	(g VSS / g VSS) / d
Endogenous Decay Co-efficient	0.06	(g VSS / g VSS) / d
True Yield Co-efficient	0.3125	g VSS / g b COD
	0.5000	g VSS / g BOD
Fraction of biomass that remains as cell debris	0.15	

Table 3: Design parameters as adopted for biological treatment in WWTPs (continued)

Parameters	Value	Unit
θ values		
Temperature activity co-efficient for K_s	1.00	
Temperature activity co-efficient for μ_m	1.07	
Temperature activity co-efficient for k_d	1.04	
Other data		
Design temperature of reactor basin	12.00	deg C
Design MLSS	8000.00	g / m^3

Ratio of VSS to TSS	0.70	
Design MLVSS	5600.00	g / m^3
Percentage clean water oxygen transfer efficiency (for fine bubble ceramic diffusers)	35.00	%
Elevation at site	9.00	m
Atmospheric pressure at elevation of site	95.60	kPa
Effective liquid depth in reactor basin	4.07	m
Point of air release for ceramic diffusers from bottom of reactor basin	0.50	m
Standard temperature	20.00	deg C
Concentration of dissolved oxygen at standard temperature & pressure of 101325 N/m^2	9.08	g / m^3
Aeration α factor for BOD removal	0.50	
Salinity & surface tension correction factor for both conditions i. e. BOD removal	0.95	
Diffuser fouling factor	0.90	
Percentage (by weight) of oxygen in air	23.20	%

Table 3: Design parameters as adopted for biological treatment in WWTPs (continued)

Parameters	Value	Unit
Density of air	1.20	kg / m^3
Oxygen transfer efficiency	8.00	%
Factor of safety	2.00	
Oxygen consumption	1.42	mg / mg of cell

2.6 COMPONENTS OF WWTPS

The major equipment and accessories as required for MBR based WWTP are enlisted below:

- Reaction Basins & Accessories
- Membrane Chambers & Accessories
- Reactor Basin Waste Transfer Pumps and Pump-House
- Internal Recirculation Pumps and Pump-House
- Mixed Liquor Recirculation Pumps and Pump-House
- Blowers and Blower Building

Primary Clarifiers and Secondary Clarifiers are not required for WWTPs with MBR.

2.7 DESIGN, DETAILING AND COST ESTIMATION

A model as delineated below has been developed in Microsoft Excel Spread Sheets to execute the tasks of designs and estimations for WWTPs with MBR:

- Process design and sizing of the major equipment and accessories based on adopted design criteria.
- Preparation of bill of quantities for the construction of designed equipment by application of algorithms assigned for basins with diffused aeration, pumping and blowers as furnished in CAPDET – USEPA (1982).
- Cost estimation of civil works (earthwork, R.C. wall in-place, R.C. slab in-place and handrails in-place) for each of all major equipment by use of Schedule of Rates (latest publication) of Public Works Department (PWD), Government of India (2021).
- Cost estimation of non-scheduled mechanical as well as electrical equipment with applicable accessories based on rates collected from vendors. A contingency @ 10 % to account for the minor cost items such as liquid piping system, control equipment, painting, site cleaning, site preparation, etc has been duly incorporated within the model.
- Determination of capital expenditure (CAPEX) and operation expenditure (OPEX) for energy consumption, operation and maintenance for 25 years of life of WWTP. Cost of

land required for installation of the complete system has been duly incorporated within the model.

The model developed requires input data such as design capacity of WWTP in MLD, concentrations of BOD_5, SS of raw wastewater and the design treated effluent BOD_5 and SS. The developed model projects the overall cost (inclusive of CAPEX, OPEX and required land with 2021 considered as base year) of MBR based WWTP for biological treatment.

3. Results and Discussion

Model algorithms developed in Microsoft Excel (2010) for detail design and estimation have been used to generate data sets for different groups comprised of plant capacities [at the capacity interval of 0.5 MLD for small group, 5 MLD for medium group and 10 MLD for large group as stated in section 2.1] and respective integrated costs inclusive of capital cost, operation as well as maintenance cost and cost of land. A summary of results derived for medium group only is presented in Annexure - 1 for typical reference.

Regression analysis of data sets for each range has been made based on different equations (viz., exponential, linear, logarithmic, polynomial and power). The cost curves with the capacities of WWTPs [as MLD] along X-axis and integrated costs of biological treatment [as ₹ (crore)] along Y-axis are plotted in Figures 3 through 5 for small, medium and large capacity range respectively. These plotted curves display the regression equations (shown within the figures) which correspond to maximum determination coefficient R^2 out of the above five types and these equations represent the cost functions for three different groups.

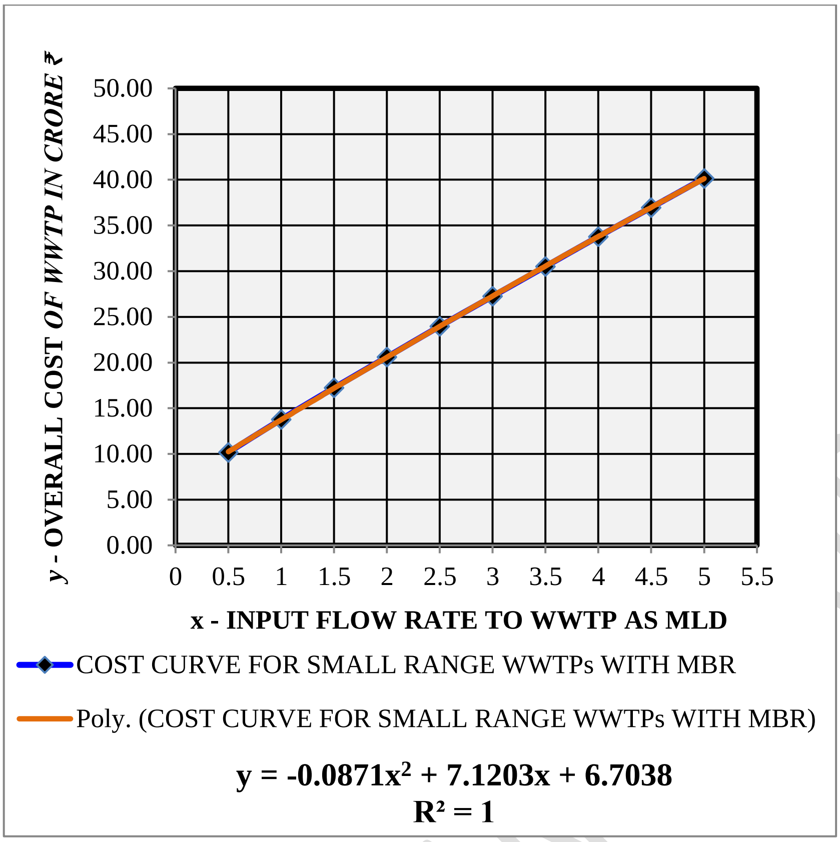

Figure 3. Cost Curve for Small Range WWTPs with MBR

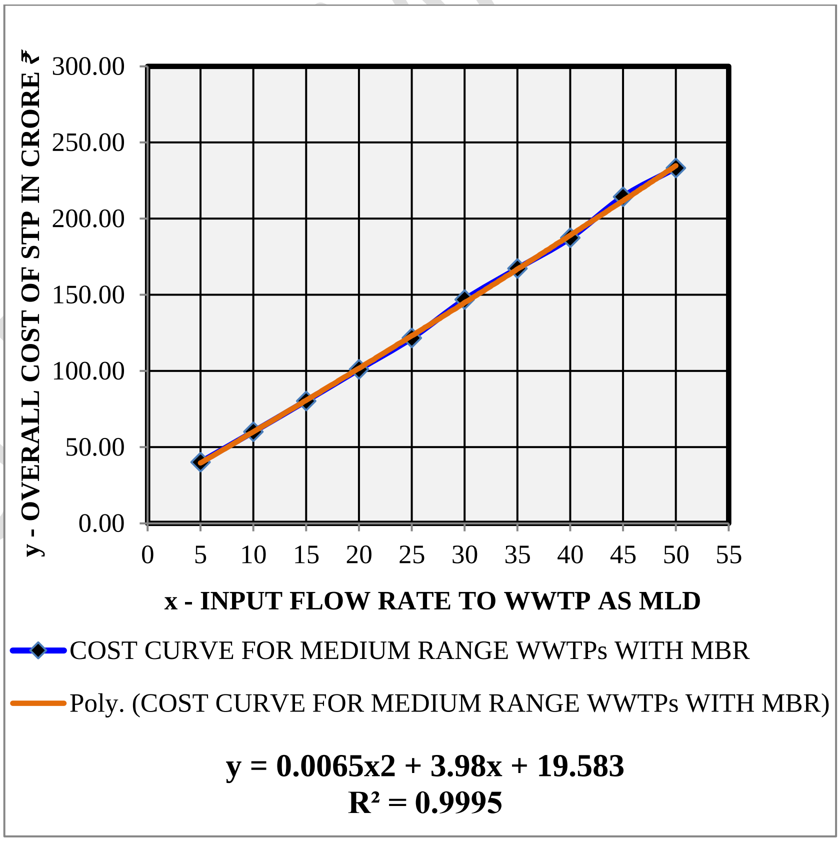

Figure 4. Cost Curve for Medium Range WWTPs with MBR

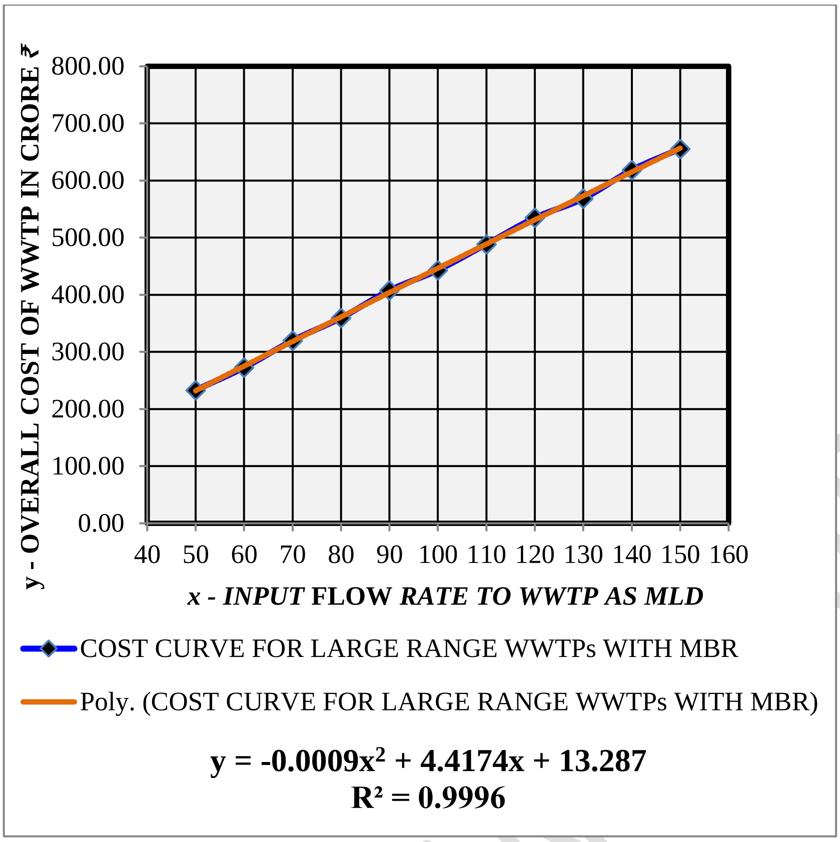

Figure 5. Cost Curve for Large Range WWTPs with MBR

The cost functions have been validated through comparison between predicted value and the respective estimated cost. Mean Absolute Percentage Error has been determined to assess the accuracy of predicted cost. MAPE is calculated as follows:

$$\textbf{MAPE} = \sum \{(|A-F|/A)*100\}/N$$

Where A= Estimated cost, F= Forecasted cost by use of cost function as determined, N= Number of elements in the data set.

The value of MAPE corresponds to the accuracy of prediction as follows:

Table 4. Interpretation of MAPE

MAPE	Interpretation
< 10	Accurate forecasting result
10 -20	Good forecasting result
20 - 50	Reasonable forecasting result

> 50	Inaccurate forecasting result

The cost functions for capacity wise three different groups of WWTPs with MBR are furnished below:

Table 5. Cost Functions for Different Groups of WWTPs

Description	***Equation***	***Value of R^2***	***Value of MAPE***
Cost function for small range WWTPs (0.5 MLD – 5 MLD)	$C_{SR} = -0.0871*(Q_{SR}^2) + 7.1203*Q_{SR} + 6.7038$	1.0000	0.18

Table 5. Cost Functions for Different Groups of WWTPs (continued)

Description	***Equation***	***Value of R^2***	***Value of MAPE***
Cost function for medium range WWTPs (5 MLD – 50 MLD)	$C_{MR} = 0.0065*(Q_{MR}^2) + 3.9800*Q_{MR} + 19.583$	0.9995	0.82
Cost function for large range WWTPs (50 MLD – 150 MLD)	$C_{LR} = -0.0009*(Q_{LR}^2) + 4.4174 *Q_{LR} + 13.287$	0.9996	0.63

Where,

C_{SR} - Cost [₹ (in crore)] of a WWTP within small range

Q_{SR} - Input flow rate [in MLD] for a WWTP within small range

C_{MR} - Cost [₹ (in crore)] of a WWTP within medium range

Q_{MR} - Input flow rate [in MLD] for a WWTP within medium range

C_{LR} - Cost [₹ (in crore)] of a WWTP within large range

Q_{LR} - Input flow rate [in MLD] for a WWTP within large range

As furnished above, the cost functions for capacity wise three different groups of WWTPs with MBR are best expressed by polynomial equations. The respective determination coefficients in respect of cost functions for capacity wise small range, medium range and large range are 1, 0.9995 and 0.9996. The respective values of MAPE with reference to the cost functions for capacity wise small range, medium range and large range are 0.18 %, 0.82 % and 0.63 %. In no case the value of MAPE has exceeded 10 %.

4. Conclusions

It is concluded that accurate forecast level cost as applicable in India could be arrived by integrated cost functions developed for capacity wise three different groups of WWTPs with MBR.

Approach with basic engineering design and cost estimations based on schedule of rates enables to achieve the high level of accuracy. Difficulties and time frame required for collection of historic cost data is not an attributing problem. The procedure as addressed in this study may be adopted to develop cost functions applicable for any region either based on use of region specific schedule of rates for accurate forecast or adjustment of projected costs (by cost functions developed) based on use of concerned country specific currency conversion factor for approximate forecast.

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Annexure – 1. A summary of results derived for medium group of WWTPs with MBR technology

DESIGN SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM											
BOD REMOVAL											
		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Average wastewater flow rate	m^3/d	5000.0	10000.0	15000.0	20000.0	25000.0	30000.0	35000.0	40000.0	45000.0	50000.0
Influent flow rate to reactor basins	m^3/d	5780.0	11560.0	17340.0	23120.0	28900.0	34680.0	40460.0	46240.0	52020.0	57800.0
Average BOD load	kg/d	1636.4	3272.8	4909.2	6545.6	8182.0	9818.4	11454.8	13091.2	14727.6	16364.0
Number of reactor basins	number	2	3	4	4	4	4	6	6	6	6
Aerobic solids residence time - design value	d	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Total volume of each reactor basin	m^3	507.97	677.29	761.95	1015.93	1269.91	1523.90	1185.25	1354.57	1523.90	1693.22
Hydraulic detention time of each reactor basin	h	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22	4.22
MLSS (X_{MLSS})	g TSS/m^3	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00	8000.00
MLVSS (X_{MLVSS})	g VSS/m^3	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14	3400.14
F/M	(g BOD/d)/g bVSS	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Volumetric BOD loading	(kg BOD/d)/m^3	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61	1.61
Total sludge (TSS) purged per day	kg TSS/d	1625.49	3250.98	4876.47	6501.95	8127.44	9752.93	11378.42	13003.91	14629.40	16254.88

Annexure – 1. A summary of results derived for medium group of WWTPs with MBR technology (continued)

DESIGN SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM											
BOD REMOVAL											
		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Design parameter	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Observed yield based on VSS	g b VSS/g bCOD	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
	g b VSS/g BOD	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Observed yield based on TSS	g TSS/g bCOD	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
	g TSS/g BOD	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Overall oxygen demand	kg oxygen/h	67.86	135.71	203.57	271.42	339.28	407.13	474.99	542.85	610.70	678.56
Air flow rate at average wastewater flow rate	m^3/min	57.84	115.68	173.52	231.36	289.20	347.04	404.88	462.72	520.56	578.40
RAS recycle ratio	-	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93	1.93
Concentration of BOD of effluent	g/m^3	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66	9.66
Concentration of TSS of effluent	g/m^3	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Concentration of NH_4-N of effluent	g/m^3	40.95	40.95	40.95	40.95	40.95	40.95	40.95	40.95	40.95	40.95
Concentration of NO_3-N of effluent	g/m^3	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5

Annexure – 1. A summary of results derived for medium group of WWTPs with MBR technology (continued)

EQUIPMENT SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM											
BOD REMOVAL											
		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Number of batteries		1	1	1	1	1	1	1	1	1	1
AEROBIC REACTOR BASINS & ACCESSORIES											
Number of reactor basins		2	3	4	4	4	4	6	6	6	6
Length of each reactor basin	m	13.64	18.19	20.46	27.28	34.11	40.93	31.83	36.38	40.93	45.47
Width of each reactor basin	m	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14	9.14
Depth of each reactor basin	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
Number of swing arm headers of each reactor basin		5	6	7	9	11	14	11	12	14	15
MEMBRANE CHAMBERS & ACCESSORIES											
Number of membrane chambers		2	3	4	4	4	4	6	6	6	6
Length of each membrane chamber	m	8.29	8.29	8.29	10.46	12.63	16.04	12.01	13.87	16.04	16.97
Width of each membrane chamber	m	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26
Depth of each membrane chamber	m	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57	4.57
Number of membrane modules provided for membrane chambers		528	792	1056	1344	1632	2016	2304	2592	3024	3312

Annexure – 1. A summary of results derived for medium group of WWTPs with MBR technology (continued)

EQUIPMENT SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM											
BOD REMOVAL											
		Capacity in mld									
		5	***10***	***15***	***20***	***25***	***30***	***35***	***40***	***45***	***50***
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE											
Total number of pumps required		2	2	2	2	2	2	2	2	2	3
Capacity of each pump	m^3/h	480.00	950.00	1420.00	1890.00	2360.00	2830.00	3300.00	3770.00	4240.00	2360.00
Area required for pump house	m ^2	65.00	71.00	76.00	82.00	87.00	93.00	98.00	104.00	109.00	115.00
BLOWERS AND BLOWER BUILDING											
Total number of blowers required		2	2	2	3	3	3	4	4	4	5
Capacity of each blower	scfm	2347.00	4569.00	6791.00	4512.00	5629.00	6768.00	5257.00	6001.00	6768.00	5635.00
Area required for blower building	m ^2	87.00	103.00	114.00	123.00	130.00	136.00	142.00	147.00	151.00	155.00

Annexure – 1. A summary of results derived for medium group of WWTPs with MBR technology (continued)

ESTIMATED COST SUMMARY FOR MEMBRANE BIOLOGICAL REACTOR BASED SYSTEM											
BOD REMOVAL											
		Capacity in mld									
		5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
AEROBIC REACTOR BASINS & ACCESSORIES											
CAPEX	Crore ₹	11.29	17.20	23.31	29.72	36.11	44.38	50.68	56.97	66.15	72.42
OPEX	Crore ₹	7.01	11.15	15.29	19.42	23.49	27.87	31.81	35.72	40.11	43.95
CAPEX & OPEX	Crore ₹	18.30	28.34	38.60	49.14	59.60	72.25	82.49	92.68	106.26	116.37
MEMBRANE CHAMBERS & ACCESSORIES											
CAPEX	Crore ₹	10.86	16.24	21.65	27.47	33.30	41.09	46.94	52.79	61.53	67.34
OPEX	Crore ₹	4.26	5.46	6.67	7.95	9.19	10.92	12.07	13.23	15.03	16.08
CAPEX & OPEX	Crore ₹	15.12	21.70	28.31	35.42	42.49	52.00	59.01	66.01	76.57	83.42
MIXED LIQUOR RECIRCULATION PUMPS AND PUMP-HOUSE											
CAPEX	Crore ₹	1.14	1.38	1.72	2.16	2.61	3.08	3.56	4.05	4.55	3.76
OPEX	Crore ₹	1.48	2.69	3.91	5.14	6.36	7.58	8.80	10.01	11.23	12.35
CAPEX & OPEX	Crore ₹	2.62	4.07	5.63	7.29	8.97	10.66	12.36	14.07	15.78	16.12
BLOWERS AND BLOWER BUILDING											
CAPEX	Crore ₹	2.76	3.91	4.83	5.54	6.26	6.92	7.78	8.38	8.96	9.88
ESTIMATED CONSOLIDATED COSTS											
CAPEX	Crore ₹	26.05	38.72	51.51	64.89	78.28	95.47	108.96	122.18	141.19	153.41
OPEX	Crore ₹	12.75	19.30	25.87	32.51	39.03	46.37	52.68	58.95	66.37	72.38
CAPEX & OPEX	Crore ₹	38.80	58.02	77.37	97.40	117.32	141.84	161.64	181.14	207.57	225.79
COST OF LAND											
Cost of land	Crore ₹	1.36	2.06	3.04	3.68	4.32	5.01	5.64	6.26	6.89	7.46
OVERALL COST											
Overall cost	Crore ₹	40.16	60.09	80.41	101.08	121.64	146.85	167.28	187.39	214.46	233.24
Overall cost	Million $	5.02	7.51	10.05	12.64	15.20	18.36	20.91	23.42	26.81	29.16

Annexure – 1. A summary of results derived for medium group of WWTPs with MBR technology (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE											
BOD REMOVAL											
		Capacity in mld									
		5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
(as per exponential cost function)											
Predicted value	Crore ₹	51.38	61.88	74.53	89.77	108.12	130.22	156.85	188.91	227.53	274.04
Value of R^2		0.9521									
Absolute percentage error	%	27.93	2.99	7.31	11.19	11.11	11.32	6.24	0.81	6.09	17.49
MAPE	%	10.25									
(as per linear cost function)											
Predicted value	Crore ₹	37.71	59.38	81.06	102.74	124.42	146.10	167.78	189.46	211.14	232.82
Value of R^2		0.9991									
Absolute percentage error	%	6.12	1.17	0.81	1.64	2.29	0.51	0.30	1.10	1.55	0.18
MAPE	%	1.57									
(as per logarithmic cost function)											
Predicted value	Crore ₹	7.37	66.06	100.39	124.75	143.64	159.08	172.13	183.43	193.40	202.33
Value of R^2		0.8933									
Absolute percentage error	%	81.64	9.94	24.84	23.41	18.09	8.33	2.90	2.11	9.82	13.26
MAPE	%	19.43									

Annexure – 1. A summary of results derived for medium group of WWTPs with MBR technology (continued)

REGRESSION ANALYSIS AND DETERMINATION OF MAPE											
BOD REMOVAL											
		Capacity in mld									
		5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
Description	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
(as per polynomial cost function)											
Predicted value	Crore ₹	39.65	60.03	80.75	101.78	123.15	144.83	166.85	189.18	211.85	234.83
Value of R^2		0.9995									
Absolute percentage error	%	1.29	0.09	0.41	0.70	1.24	1.37	0.26	0.95	1.22	0.68
MAPE	%	0.82									
(as per power cost function)											
Predicted value	Crore ₹	36.34	62.53	85.90	107.60	128.14	147.80	166.76	185.14	203.03	220.49
Value of R^2		0.9903									
Absolute percentage error	%	9.52	4.07	6.82	6.45	5.34	0.65	0.31	1.20	5.33	5.47
MAPE	%	4.52									

Where

CAPEX	:	Total bare construction cost
OPEX	:	Levelized cost based on energy requirement, operation and maintenance for 25 years of life of STP
MAPE	:	Mean absolute percentage error
R	:	Determination coefficient
Conversion rate	:	80.00 ₹ is equivalent to 1.00 $