Nutrient removal process selection for planning and design of large wastewater treatment plant upgrade needs

M. Urgun-Demirtas, K. R. Pagilla, T. E. Kunetz, J. P. Sobanski and K. P. Law

ABSTRACT

A protocol to select nutrient removal technologies that can achieve low nutrient effluents (total nitrogen (TN) < 5 mg/L and total phosphorus (TP) < 0.5 mg/L) was developed for different wastewater treatment plant (WWTP) sizes based on the research conducted during a Water Environment Research Foundation funded project. The adaptable protocol includes technology and cost assessment of feasible (pre-screened) nutrient removal technologies that are being successfully implemented at full scale. The information collected from the full scale nutrient removal plants to develop this protocol includes design, operational, performance, and cost data through a direct survey of plants, and published data. The protocol includes a "technology threshold" approach consisting of Tier I (TN < 5.0 mg/L; TP < 0.5 mg/L) and Tier II (TN < 3.0 mg/L; TP < 0.1 mg/L) effluent nutrient levels for different plant sizes. A very large WWTP (1,250,000 m^3/day flow) in Chicago, Illinois, USA adapted this protocol for master planning and design of future nutrient removal facilities based on plant and site specific criteria.

Key words | design, nutrient removal, planning, technology assessment

M. Urgun-Demirtas
K. R. Pagilla (corresponding author)
Department of Civil, Architectural and Environmental Engineering,
Illinois Institute of Technology,
3201 S. Dearborn Street, Chicago, IL 60616,
USA
E-mail: *pagilla@iit.edu*

T. E. Kunetz
J. P. Sobanski
Metropolitan Water Reclamation District of Greater Chicago, 100 E. Erie Street,
Chicago, IL 60611,
USA

K. P. Law
CTE-AECOM, 303 E. Wacker Drive. Suite 600,
Chicago, IL 60601,
USA

INTRODUCTION

There is a need to systematically assess the feasibility of proven and cost effective technologies achieving low total nitrogen (TN) and total phosphorus (TP) levels for implementation at treatment facilities of different sizes and types. This paper presents a protocol developed during a Water Environment Research Foundation (WERF) project by the authors, M. Urgun-Demirtas and K. R. Pagilla, on technology and cost assessment of successful nutrient removal technologies being currently implemented in full scale wastewater treatment plants (WWTPs) to develop a feasible list of sustainable technologies. Additionally, a case study of a very large WWTP (1,250,000 m^3/day-flow rated North Side Water Reclamation Facility in Chicago, Illinois, USA) applying an adaptation of the above-mentioned protocol for nutrient removal process selection for master planning purposes is presented in this paper. Owing to the uncertainty in projecting future regulations for TN and TP, a "technology threshold approach" has been adopted to identify alternative processes to meet the future limits.

The "technology threshold approach" involves screening and identification of the technologies that can reliably achieve low TN and TP effluents on a sustainable basis. Initial screening of alternative technologies involved identification of 15 alternative nutrient removal methods based on technology, process and economic criteria. The identification of alternative treatment technologies was accomplished primarily based on achievable effluent levels, performance, and cost data collected from the succesful treatment plants achieving low TN and/or TP levels in their effluent on a sustainable basis, as well as data and other information published in the literature (Pagilla *et al.* 2006). Subsequent ranking of the

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alternatives was based on technology and cost assessment including weighted factors that reflect the importance of the selected criteria (shown in Table 1) in relation to one another. This protocol allows site-specific and plant specific criteria to be given more importance for the purpose of screening, evaluation and selection of successful nutrient removal technologies. The protocol was used to list appropriate processes and their ranking for different typical size plants, such as, 100 mgd (378,500 m^3/day), 50 mgd (189,250 m^3/day), 10 (37,850 m^3/day), and 1 mgd (3,785 m^3/day). The results from large WWTPs (>50 mgd) technology and cost assessment are presented in this paper.

METHODOLOGY

Selection of nutrient removal technology alternatives

Technology criteria were used to evaluate the capability of an alternative technology to meet the objectives of this study on a consistent basis (Table 1). For treatment criteria, two levels of effluent quality were considered. The "moderate" threshold includes effluent TN < 5.0 mg/L and TP < 0.5 mg/L limits (Tier I), and the "more stringent" threshold is for effluent TN < 3.0 mg/L and TP < 0.1 mg/L (Tier II) limits. Maintability and operability criterion is based on the available information on maintenance and operation and associated costs for each treatment alternative. Energy efficiency ranking included both energy requirement calculations and published information. Historical performance was a key factor in assessing reliability and sustainability ranking of each treatment alternative. The impact of each alternative on the environment such as comfort and safety of neighbours was determined based on the analysis of its design layout. Expandability of each alternative is evaluated by the selected process' ability to meet future stringent levels of N and P. Higher scores are given to more favourable criteria and higher weighting to more desirable criteria.

Table 1 | Evaluation criteria for technology and cost assessment of screened treatment alternatives. The weights are typical values for an example plant used for analysis purposes during this study

Technology criteria (total score = 200 points)		Cost criteria (total score = 170 points)	
Criterion	**Weight**	**Criterion**	**Weight**
Ability to achieve desired effluent limits	5	PW Cost	5
Maintability & operability	4	Construction cost	3
Reliability & sustainability	3	Annual O & M cost	3
Expandability	3	Unit cost $/1,000 gal	4
Energy efficiency	3	Land requirement	2
Impact on neighbors	2		

Cost criteria were used to compare the cost of implementing the technologies being investigated (Table 1). Since plant capacity has a significant impact on the cost of the treatment, a conceptual cost analysis for each technology alternative has been formulated based on the flow rate range. USEPA cost estimating techniques were used for cost calculations because of limited plant cost data and its variability due to site specific conditions (USEPA 1998). The cost analysis is broken down into capital costs and operation and maintenance costs to determine present worth (PW) cost of the treatment alternatives. Capital costs include those for construction, engineering, site work and piping, subsurface considerations, legal, fiscal and administrative services, interest during construction and land requirement. Operation and maintenance requirements are determined individually for three categories: energy, maintenance, and labor. Since the cost values are site-specific, US nationwide costs as specified in USEPA Manual (1978) were used during the cost analysis. All costs were updated to 2007 using engineering news record (ENR) construction cost index. The unit N and P removal cost for each alternative was also calculated from the PW cost analysis.

Development of scoring matrix and evaluation of alternative treatment systems

A scoring matrix was developed for alternatives assessment using ratings ("10" for the most positive to "1" for the least positive) and weights from 1 to 5 depending on its relative importance to the initial screening of alternative technologies. The ratings and weights used in this analysis are based on the engineering judgement of the authors for a typical plant, and are not specific to any plant. The scores for technology (total 200 points) and cost (total 170 points) criteria for each alternative are added to arrive at a total score for each alternative.

First, the design basis of each alternative treatment process was determined from the published literature and plant data (Sedlack 1991; WEF 1998; Pagilla *et al.* 2006). Instead of the detailed plant process design, an approximate unit process design with an estimated capital and operating costs was developed for each treatment option to establish an order for ranking each treatment alternative. In capital cost calculations, tank volumes, mixing requirements, and recirculation pump costs were major factors, and chemical costs were a significant contribution to the operating costs, particularly, in case of Tier II alternatives. In addition, chemical costs were based on current prices, chemical sludge disposal costs were included in the operational factors, and recirculation rates were set at 50% of installed recirculation pumping capacity for operating cost estimation.

RESULTS AND DISCUSSION

Assessment of treatment alternatives for future stringent levels

The treatment alternatives were ranked based on the results of the scoring matrix developed (Table 2). For example, Johannesburg with high internal recirculation (IR), Bardenpho type process, UCT/VIP with high IR, and chemical-P removal + Denite (deN) filters with sand filtration are the highest ranked processes for achieving Tier I and Tier II limits for plant sizes in the 189,250 m^3/day range. It can be seen from Table 2 that the top ranked technologies alternatives for both Tier I and Tier II primarily include BNR processes that can be operated in multiple modes.

Case study of North Side WRP nutrient removal master planning and design

North Side WRP is a combined sewer flow WWTP that includes single-pass and two-pass aeration tanks and circular clarifiers in the AS process. The primary effluent at North Side WRP is relatively dilute in strength (BOD_5 = 83 mg/L), but the BOD_5/TKN (4.4) and BOD_5/TP (38) ratios indicate that the North Side WRP wastewater is compatible with biological nutrient removal processes. The current effluent discharge permit limits include $cBOD_5$ = 10 mg/L; TSS = 12 mg/L; NH_4-N = 4.0 (Nov to Mar)/2.5 mg/L (Apr to Oct) on monthly average basis. The nutrient removal technology alternative evaluation protocol and scoring matrix were

Table 2 | Evaluation of treatment alternatives for 189,250 m^3/day (50 mgd) plant capacity

	Tier I				Tier II			
Alternative	Cost score	Technology score	Total score	Rank	Cost score	Technology score	Total score	Rank
Johannesburg high IR + chem-P + sand filter	**166**	**120**	**286**	**1**	**140**	**120**	**260**	**2**
Bardenpho + chem-P + sand filtration	**135**	**140**	**275**	**2**	**127**	**140**	**267**	**1**
Modified Bardenpho + chem-P + sand filter	**133**	**133**	**266**	**3**	**125**	**133**	**258**	**3**
Modified Bardenpho with fermenter + sand filter	**133**	**133**	**266**	**3**	**125**	**133**	**258**	**3**
Johannesburg + chem-P + deN filter	**131**	**120**	**251**	**5**	113	120	233	6
UCT/VIP high IR + chem-P + sand filter	139	111	250	6	**131**	**111**	**242**	**5**
Johannesburg + fermenter + deN filter	134	109	243	7	110	109	219	8
UCT/VIP + chem-P + deN filter	119	105	224	8	103	105	208	11
Step feed + chem-P + deN filter	103	119	222	9	110	119	229	7
UCT/VIP + fermenter + deN filter	119	101	220	10	103	101	204	12
AS with Nitr. + deN filter + chem-P	73	139	212	11	78	139	217	9
MLE/IFAS high IR + chem-P + sandfilter	99	111	210	12	101	111	212	10
AS with Nitr. + Denit. + chem-P + sand filter	76	131	207	13	63	131	194	13
MLE/IFAS + chem-P + deN filter	90	108	198	14	80	108	188	14
AS with Nitr. + Denit. + Phostrip + chem-P + sand filter	44	94	138	15	34	94	128	15

Table 3 | Recommended nutrient removal alternatives for North Side WRP

2020 Alternatives (moderate threshold)	Rank	2040 Alternatives (stringent threshold)	Rank
MLE with Chem-P and effluent filtration	1	MLE with high IR plus Chem-P and effluent filtration	1
Modified step-feed with anoxic zones plus Chem-P and effluent filtration	2	Modified step-feed with larger anoxic zones plus Chem-P and effluent filtration	1
Bardenpho (operated at low IR) with Chem-P and effluent filtration filtration	3	Bardenpho with Chem-P and effluent	3
Johannesburg with Chem-P and effluent filtration	4	Modified Bardenpho with Chem-P and effluent filtration	4
MLE with high potential IR (but operated at low IR) plus Chem-P and effluent filtration	4	Denitrification filter with Chem-P	5

applied to the North Side WRP as part of the facility's master planning process. Due to uncertainty of the future effluent nutrient limits, two thresholds were considered for the purpose of master planning. The "moderate" threshold includes effluent TN of $6 \sim 8$ mg/L (7 mg/L used in calculations) and 0.5 to 1.0 mg TP/L (0.5 mg/L used in calculations), and the "more stringent" threshold is effluent with < 5.0 mg TN/L (3 mg/L used in calculations) and <0.5 mg TP/L (0.1 mg/L used in calculations). The recommended short listed alternatives for the Year 2020 (moderate threshold) and Year 2040 (stringent threshold) are shown in Table 3. The recommended alternatives for Year 2020 are processes that are easily upgradeable to the recommended multiple-stage alternatives for the Year 2040.

CONCLUSIONS

In this study, the developed process selection protocol significantly updates the systematic approach for nutrient removal process selection and allows inclusion of site-specific factors such as those seen in the case study for North Side WRP. The North Side WRP case study showed that this systematic protocol can be used successfully for planning and selection of nutrient removal processes.

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