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Financial analysis of NF membranes for upgrading municipal wastewater treatment

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ABSTRACT

Nanofiltration (NF) membranes represent state-of-the-art membrane processes with numerous significant applications. In this paper, worldwide reported financial data on capital, operating (O&M) and unit costs were gathered, screened, and analyzed. New cost functions have been developed incorporating plant capacity and NF recovery. Further, software (NFSTP) was developed for performance and cost evaluation from the verified models. Analysis of the data represented by NF cost models indicate that the unit cost of NF treatment for secondary treated wastewater decreases by about 11%, when plant capacity is doubled from 50,000 to 100,000 m^3/d for the same recovery. Moreover, the change in recovery above 70% would not significantly affect the capital, O&M, and unit costs. Application of NF system to the case of El-Gabal El-Asfar municipal wastewater treatment plant in Egypt using the developed software (NFSTP) indicates a unit cost of 0.253 $\$/m^3$ for an operational module of 100,000 m^3/d.

Keywords: Nanofiltration; Upgrading; Municipal wastewater; Unit cost; Cost functions

1. Introduction

Wastewater reuse presents a promising solution to overcome the shortage of fresh water resources, but it requires an efficient economic feasible treatment processes to achieve high water quality [1]. Reclaimed wastewaters can be used in irrigation, industrial applications (e.g. cooling water), and urban development [2,3]. Treatment methods for municipal wastewater include physical, chemical, and biological methods through four stages; preliminary, primary, secondary, and tertiary treatment as well as membrane separation processes which are recently used for wastewater treatment. Membrane bioreactor is a promising technology for sewage treatment, producing a suspended solid-free effluent [4,5].

Tertiary treatment is an advanced treatment to improve water quality through chemical adsorption, filtration, and membrane treatment. Reverse osmosis

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(RO) or Nanofiltration (NF) is always recommended as a barrier for contaminants in the reclaimed water [6]. RO can offer the effective removal of most dissolved constituents and it is considered as an energy extensive process due to its high operating pressures [7]. NF membranes remove materials as small as 250 (Dalton) in molecular weight which is typically used in softening, disinfection, and removal of dissolved organics and metals [8]. Latest generation of NF membranes provide lower feed pressures and operating costs than RO membranes with similar permeate water quality. Lower feed pressures result in potential savings of \$ 0.03–0.08/m^3 for treating reclaimed water [9]. Cost estimation is an important aspect in the treatment of wastewater. Cost is going to escalate continuously over time so that it may require advanced and comprehensive evaluation with regard to economic feasibility in the future planning. Previous cost analysis with respect to wastewater treatment has focused primarily on capital costs and associated differences with facility size. Formulation of cost functions has been proposed by many authors to predict tertiary treated wastewater using membranes [10] and the construction cost of tertiary domestic wastewater treatment using fuzzy regression models [11]. Gonzalez et al. analyzes the effectiveness and cost of wastewater treatment options for uses of reclaimed water [12]. Hernández-Sancho and Garrido studied the technical efficiency and cost analysis in wastewater treatment processes [13]. Friedler and Pisanty studied the effect of design flow and treatment level on construction and operating costs of municipal wastewater treatment plants [14].

This paper is concerned with the development and verification of cost models for upgrading secondary treated wastewater (STWW) using NF based on reported worldwide data. Further, software was developed for predicting NF performance (performance functions were previously developed by the authors [15]) as well as financial indicators which has been experimentally tested for the potential applications of NF system for El-Gabal El-Asfar WWTP in Egypt.

2. Approach and methodology

2.1. Approach

The adopted approach enables the development of a simple cost model for NF tertiary treatment system for STWW. The preliminary design cost estimate determines the financial indicators including capital, annual O&M, and unit costs of NF system. Relevant worldwide reported NF cost data on large-scale facilities for upgrading STWW have been collected, screened, analyzed, and correlated for the development of empirical cost models. Extensive field surveys for capital and O&M costs have been undertaken for large-scale Egyptian secondary wastewater treatment plants to enable assessment and prediction of NF system costs. These models have been utilized to develop and test quick decision-making regarding capital and O&M cost requirements for medium and large NF plants treating STWW.

2.2. Methodology

Developed empirical correlations comprised estimation of NF permeates compositions and pertinent capital, annualized O&M and unit costs have been collected. Thus, data streams (sets) on performance and costs have been subjected to refining and processing using non-linear regression technique. The empirical formulation has been verified using appropriate selective data-sets on similar plants. Visual database (ver. 7.01) has been used to build a friendly software enabling rapid estimation of NF permeate quality and costs. The input data of the software include plant capacity in (m^3/d), system recovery (R %), the selected NF membrane cutoff (Da), operating pressure (psi), as well as feed water characteristics. This developed software has been applied to predict NF performance using the previously developed correlation by the authors [15] as well as financial indicators for one of the STWW plants in Egypt. Cost data are adjusted using cost index of Engineering News Record (index) for 2013 [16].

3. Results and discussion

3.1. Cost analysis for NF tertiary treatment

Table 1 represents the relevant worldwide reported data adopted for formulating the capital and O&M cost equations for NF tertiary treated STWW [17–23]. The capacities involved in this study vary from 10,200 to 193,750 m^3/d and recoveries from 65 to 90%. Analysis of the available data suggests that the most important factors affecting empirical cost estimation are capacity (Q) and NF recovery (R %).

3.2. Developed NF cost models for STWW

Amortized capital, O&M, and unit cost model formulations using non-linear regression analysis are presented below:

$$C_{\text{A.capital}} = 0.9 \times (Q)^{-0.24} \times (R)^{0.087} \quad (1)$$

Table 1
NF cost data for treatment of surface water and STWW [17–23]

Plant	Plant capacity (m^3/d)	Amortized capital cost ($/$m^3$)	Annual O&M cost ($/$m^3$)	Unit cost ($/$m^3$)	Recovery *R* %	Year
Florida	10,200	0.204	0.264	0.468	90	1993
Florida	16,300	0.201	0.259	0.460	88	1996
OKLAHOMA	18,000	0.192	0.243	0.435	75	2010
Florida	21,364	0.189	0.231	0.420	88	1996
California	26,495	0.168	0.226	0.394	75	2008
Finland	27,000	0.154	0.221	0.375	68	2006
BROWARD	37,850	0.149	0.217	0.366	85	2002
California	50,000	0.148	0.213	0.361	75	2008
Florida	65,830	0.147	0.210	0.357	88	1996
Florida	82,650	0.143	0.208	0.351	88	1996
Florida	94,625	0.134	0.205	0.339	88	1996
Portugal	100,000	0.125	0.198	0.323	75	2006
North Bay Regional	123,000	0.126	0.190	0.316	85	2008
Finland	132,650	0.124	0.182	0.306	70	2006
California	150,000	0.122	0.174	0.296	75	2008
Venice	171,300	0.119	0.169	0.288	85	2005
Venice	193,750	0.098	0.161	0.259	85	2005

$$C_{\text{O\&M}} = 1.24 \times (Q)^{-0.14} \times (R)^{-0.076} \quad (2)$$

$$C_{\text{unit}} = C_{\text{A.capital}} + C_{\text{O\&M}} \quad (3)$$

where $C_{\text{A.capital}}$: amortized capital cost ($/$m^3$), $C_{\text{O\&M}}$: amortized O&M cost ($/$m^3$), C_{unit}: unit cost ($/m^3), Q: plant capacity (m^3/d), and R: NF membrane recovery (%).

The O&M costs include costs for energy, labor, membrane replacement, chemicals, and maintenance. Unit cost is the sum of amortized capital and (O&M) costs in $/$m^3$ of produced treated water. The developed cost models have been verified using selected reported data of large-scale NF treatment plants for STWW or surface water [17–23]. The developed cost models are in good agreement with the actual data as shown in Figs. 1–3 with deviation up to 11%.

3.3. Effect of NF system capacity and recovery on cost indicators

Figs. 4–6 show the effect of system recovery (65–90%) on the amortized capital and O&M costs at different ranges of capacities (10,200–100,000 m^3/d). The data reveal the decrease in costs by increasing plant capacities. Increasing the recovery for the same capacity slightly increases the capital and O&M costs. Estimated amortized capital and O&M costs for NF tertiary treated STWW plants for capacities 50,000 and 100,000 m^3/d at different NF membrane recoveries are shown in Fig. 7, where amortized O&M costs are higher than amortized capital costs and significant decrease in amortized capital and O&M costs is observed by increasing the capacity. Slight change of costs is observed by increasing recoveries from 65 to 85% where, by doubling the capacity, cost reductions of amortized capital, O&M, and unit costs are in the range (14.2–14.9%), (3.1–4.3%), and (11.6–12.6%), respectively, as shown in Table 2.

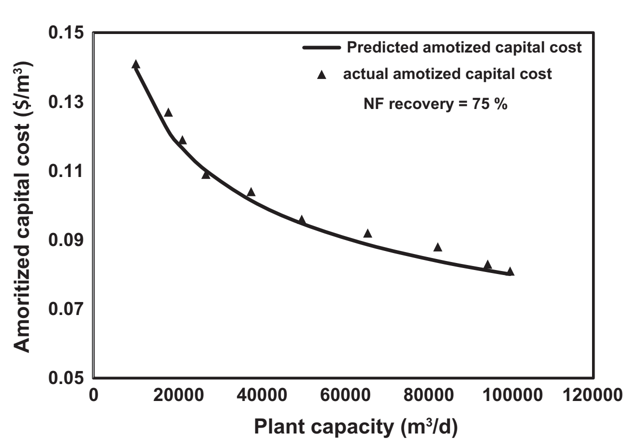

Fig. 1. Predicted vs. actual amortized capital costs.

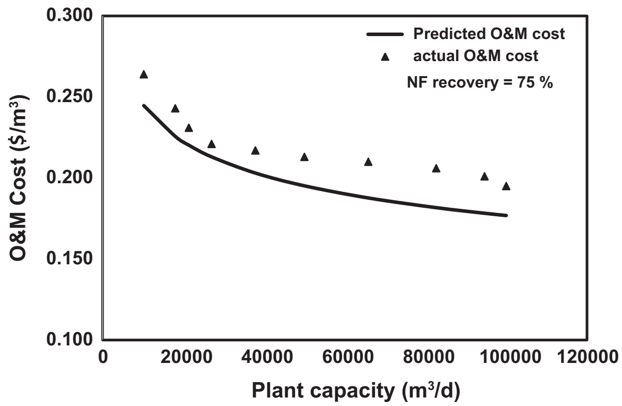

Fig. 2. Predicted vs. actual O&M costs.

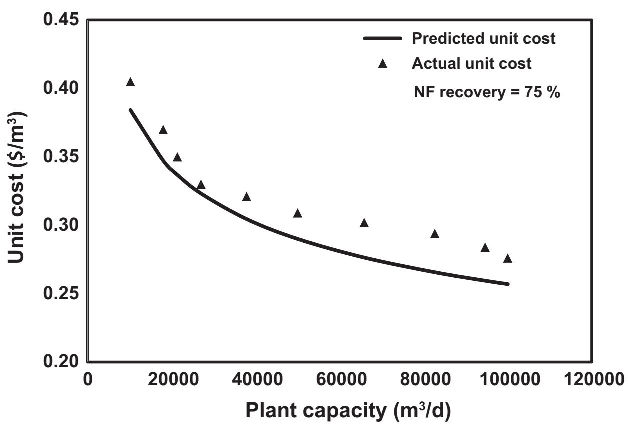

Fig. 3. Predicted vs. actual unit costs.

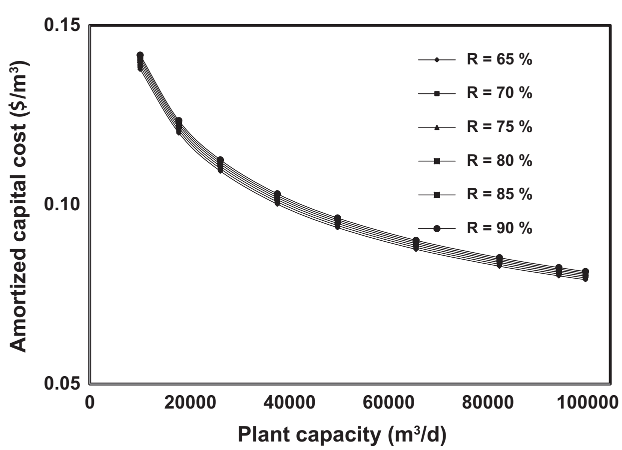

Fig. 4. Effect of NF system recovery on amortized capital cost.

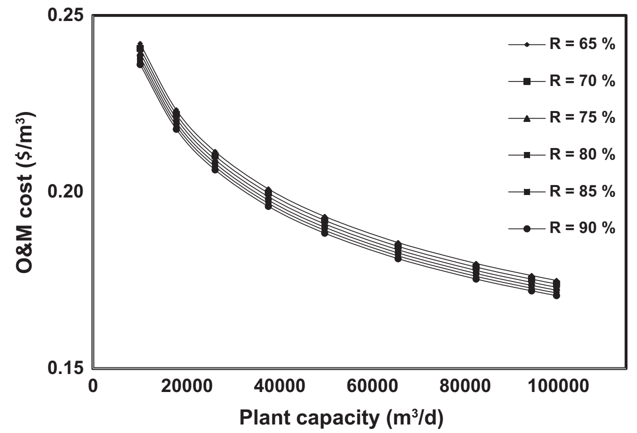

Fig. 5. Effect of NF system recovery on O&M cost.

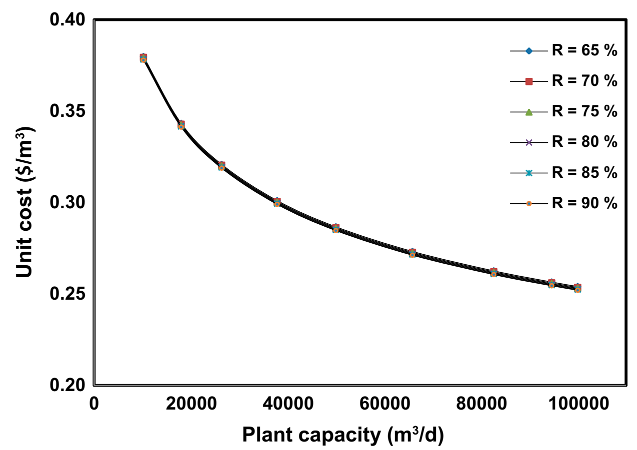

Fig. 6. Effect of NF system recovery on unit cost.

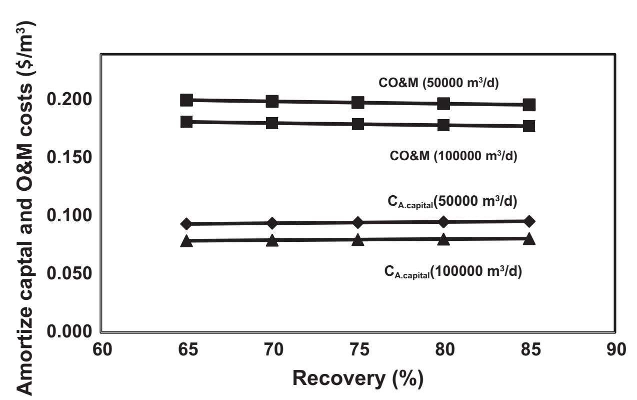

Fig. 7. Effect of NF recovery on amortized capital and O&M costs for capacities 50,000 and 100,000 m^3/d.

Table 2
Estimated costs reduction for NF treatment of STWW plant at 50,000 and 100,000 m^3/d

	Cost reduction (%)		
Recovery (%)	Amortized capital cost	O&M cost	Unit cost
65	14.2	4.3	12.6
70	14.3	4	12.3
75	14.5	3.8	12
80	14.7	3.5	11.8
85	14.9	3.1	11.6

Table 3
Predicted performance of NF treatment for El-Gabal El-Asfar STWW plant (100,000 m^3/d)

	Composition (mg/l)		
Item	Feed (STWW)	Predicted NF permeate	NF rejection (%)
COD	45.5	5.11	88.8
P+3	0.488	0.014	97
Ca+2	23.75	1.475	93.8
Cu+2	0.021	0.002	90.5
Fe+2	0.723	0.108	85
Mn+2	0.006	0.000	100.0
Na+	3.01	0.083	97.2
Ni+2	0.023	0.001	95.7
Zn+2	0.011	0.001	90.9

3.4. Developed software for NF treating STWW

An interactive software for NF treating STWW (NFSTP) was developed to predict NF permeate quality with relevant financial indicators. The input data of the software include plant capacity in (m^3/d), system recovery (R %,) the selected NF membrane cutoff (Da), operating pressure (psi), as well as feed water characteristics of STWW.

3.5. NF permeate characteristics and financial indicators for El-Gabal El-Asfar plant

The developed (NFSTP) program is used in the design stage as a shortcut estimation method for NF membrane system treating STWW of El-Gabal Al-Asfar WWTP with a capacity of 100,000 m^3/d, NF recovery of 75%, NF cutoff (200 Da), and operating pressure of 75 psi. The inlet and predicted effluent characteristics of El-Gabal Al-Asfar STWW are shown in Table 3. The output results of NFSTP software for the suggested plant cost estimation are: 38.8×10^6 \$, 0.08 \$/m^3, 5.88×10^6 \$/year, 0.173, and 0.253 \$/m^3 for capital, amortized capital, annual O&M, amortized O&M, and unit costs, respectively. It is observed that the treatment capital cost using NF system is relatively high within the current technology and cost estimation model. Additional work is still needed to optimize NF plants through increasing local inputs and improving overall process integration.

4. Conclusion

NF plants are emerging technologies that provide additional testing treatment for STWW. Worldwide performance and cost data have been analyzed and assembled in friendly software enabling quick prediction of NF permeate quality and essential financial indicators. Analysis of the effect of NF recovery and plant capacity confirms only on significant reliance on plant capacity for recoveries exceeding 70%. Moreover, evaluation of potential applications of NF system to El-Gabal El-Asfar WWTP manifests a reasonable treatment economics for an operational NF module of 100,000 m^3/d. The pertinent capital, annual O&M, and unit costs are 38.8×10^6 \$, 5.88×10^6 \$/year, and 0.253 \$/m^3, respectively. Additional effort is still needed to improve the financial setting of NF plants to cope with conditions in developing countries.

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