Preliminary Cost Estimation Models for Construction, Operation, and Maintenance of Water Treatment Plants

Jwala R. Sharma, Ph.D., M.ASCE[1]; Mohammad Najafi, Ph.D., P.E., F.ASCE[2]; and Syed R. Qasim, Ph.D., P.E., M.ASCE[3]

Abstract: Reliable cost estimation of construction, operation, and maintenance (O&M) of water treatment plants is essential for project planning and design. The authors have developed construction and O&M cost models for different unit operations and processes involved in water treatment plants. These models are developed from historical cost data and can be used to develop preliminary cost estimates for major project components and to screen alternative process trains of a water treatment project during the planning phases of the project. The historical cost data were updated to April 2011 costs by using cost indexes from Engineering News Record (ENR) and Bureau of Labor Statistics (BLS), in addition to April 2011 costs of energy and labor. This paper presents the use of a single cost index to further update construction and O&M costs. This approach has significant advantages over using multiple indexes (such as ENR and BLS indexes) for different cost components. Using the method presented in this paper, future cost updating by ENR construction and building cost indexes becomes simple and straightforward. Actual bid prices for one new water treatment plant construction and two water treatment plant expansion projects were obtained from reputed consulting firms and compared to estimated costs by using the cost models presented in this paper. Further validation is recommended by use of the equations and comparisons of the costs to the detailed estimates and actual bids. Accurate forecasting of the costs of a project is site specific and cannot be generalized. Design plans and specifications are needed to develop accurate cost estimates based on equipment, materials, and labor. **DOI:** 10.1061/(ASCE)IS.1943-555X.0000155. *© 2013 American Society of Civil Engineers.*

CE Database subject headings: Water treatment plants; Construction costs; Maintenance; Costs.

Author keywords: Construction costs; Operation and maintenance costs; Water treatment plants; Cost estimation.

Introduction

Reliable construction, operation, and maintenance (O&M) costs of water treatment plants are essential for proper project planning, design, and construction. During the planning phases of the project, preliminary cost estimates are developed for major project components and alternative process trains. These estimates are used to verify the feasibility of the project and whether the project budget is adequate. At this stage, design modifications can be made and compared to evaluate process options and select the most cost-effective alternative. These estimates are also useful for arranging project funding and securing engineering design services (Kawamura 2000; Qasim et al. 1992).

Detailed construction cost estimates are developed after completion of the design phase of the project. These cost estimates are valuable to compare and evaluate bids received for construction of the project. These costs utilize accurate estimates based on quantities of work and materials based on manufacturers' data on current pricing, parts, and labor. Many factors that influence the detailed costs include: (1) plant capacity; (2) design criteria and permit costs; (3) raw water quality; (4) treatment processes; (5) equipment and installation; (6) electrical work and instrumentation; (7) site conditions, land costs, and climate; (8) competition among the bidders and suppliers; and (9) general local and national economic conditions. For these reasons, the detailed construction and O&M costs cannot be generalized and must be developed when the project design and specifications have reached the final stages (Qasim et al. 2000).

There is a need to develop reliable preliminary cost data for the project planning phase. Gumerman et al. (1979), in a four-volume EPA report, proposed generalized construction and O&M cost curves. The use of these cost curves requires visually determining the construction and O&M costs of treatment unit based on the treatment unit capacity. Thus, determined costs are in 1978 dollars and need to be updated to costs that are relevant to the date of estimate. Therefore, these cost curves are time consuming to use and prone to human errors. Qasim et al. (1992) used the cost data from the work of Gumerman et al. (1979) to propose a series of polynomial equations to represent generalized construction and O&M costs of 1978. These equations received wide applications, despite limitations in cost updating. The cost equations required the use of cost indexes from both *Engineering News Record* (ENR) and the Bureau of Labor Statistics (BLS) to update costs of eight different cost components. Eight construction cost components were utilized: excavation and site work (A); manufactured equipment (B);

[1]EIT, Project Engineer, Ph.D. Candidate, Laney Directional Drilling Co., 2031 Humble Place Dr., Humble, TX 77338 (corresponding author). E-mail: jsharma@laneydrilling.com

[2]Director, Construction and Infrastructure Engineering and Management, CUIRE Director, Dept. of Civil Engineering, Univ. of Texas at Arlington, Box 19308, 428 Nedderman Hall, Arlington, TX 76019-0308. E-mail: najafi@uta.edu

[3]Professor Emeritus, Dept. of Civil Engineering, Univ. of Texas at Arlington, Box 19308, 428 Nedderman Hall, Arlington, TX 76019-0308. E-mail: qasim@uta.edu

Note. This manuscript was submitted on November 11, 2011; approved on March 4, 2013; published online on March 6, 2013. Discussion period open until May 1, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Infrastructure Systems***, Vol. 19, No. 4, December 1, 2013. © ASCE, ISSN 1076-0342/2013/4-451-464/$25.00.

concrete (C); steel (D); labor (E); piping and valves (F); electrical equipment and instrumentation (G); and housing (H). Using the BLS producer price index (PPI) is complicated because BLS changed the basis for cost indexing in 1978 and 1992 (Bureau of Labor Statistics 1978, 1992a, b), so the costs may be updated by using revised indexes for categories in which the basis for indexing is changed. On the other hand, ENR does not publish different cost indexes for application in different construction cost components.

This paper presents cost equations that represent construction and O&M costs of April 2011 and can be further updated by using a single index. The key advantage of a single index is the simplicity with which it can be applied. The most frequently utilized single indexes in construction industry are the ENR construction cost index (CCI) and the ENR building cost index (BCI). The difference between CCI and BCI is in the labor component. The CCI uses 200 h of common labor, whereas the BCI uses 68.38 h of skilled labor, including bricklayers, carpenters, and structural ironworkers. The most important advantages of ENR indexes are their availability, simplicity, and geographic specificity. In this paper, complications presented by BLS changes in the basis for indexing, and the unavailability of ENR cost indexes for many categories for water treatment plants, have been overcome by allowing cost updating by a single ENR cost index.

Cost Indexes

The use of cost indexes is the most common method to update cost estimates from one geographic location and time to another (Qasim et al. 1992). Project planners and estimators frequently make quick order of magnitude cost estimates of a project by using scale-up factors (indexes) on previous, similar projects to adjust for time and location (Remer et al. 2008). A cost index for a location and time is a number that represents the relative cost of a commodity and/or service with respect to a given base location and time. Remer et al. (2008) reported that the first cost indexes were developed in 1750 and that the ENR is the oldest cost index that is currently used by engineers. Remer et al. (2008) also enlisted approximately 46 cost indexes currently in use in the U.S. These indexes can be used for adjusting construction, labor, education, and retail costs. It is important to use the correct index for particular cost updates. ENR publishes the CCI and BCI. Current ENR indexes can be obtained from the ENR website (http://enr.construction.com/economics/default.asp) or from the most recent issue of ENR. Likewise, BLS indexes can be obtained from the BLS website (http://www.bls.gov). Other indexes available for such cost updates are the Bureau of Reclamation, Federal Highway Administration (FHWA) construction bid price index, Handy-Whitman public utility construction cost index, Means building construction cost index, and the Richardson construction cost trend reporter.

Generalized Construction Costs

Gumerman et al. (1979) utilized equipment cost data supplied by manufacturers, cost data from actual plant construction, and unit takeoffs from actual and conceptual designs to develop generalized construction costs of treatment processes. In this paper, the construction cost data developed by Gumerman et al. (1979) have been updated to April 2011 costs by using both ENR and BLS indexes available in Engineering News Record (1978, 2011) and Bureau of Labor Statistics (2011) respectively. The indexes used to update these cost data and applicable cost components are given in Table 1. The generalized construction costs do not include such costs such as (1) special sitework; (2) markups from general contractors for overhead and profit; (3) engineering design and inspection support, land, legal, fiscal, and administrative costs; or (4) financing costs. These costs are related to overall project costs rather than to a particular treatment process. Therefore, designers must add these costs to the total construction costs of the treatment process involved.

Table 1. Indexes and Prices Used to Update Construction and O&M Costs

Cost component	Index	October 1978 value of index	Modified october 1978 value of index/price	Updated april 2011 value of index/price
Total cost	ENR CCI	265.38 (1967 = 100)	2,859.0 (1913 = 100)	9,027.23 (1913 = 100)
Excavation and site work (A)	ENR skilled labor wage index	247.0 (1967 = 100)	2,467.8 (1913 = 100)	8,652.25 (1913 = 100)
Manufactured equipment (B)	BLS general purpose machinery and equipment (Commodity Code 114)	221.3 (1967 = 100)	72.9 (1982 = 100)	206.2 (1982 = 100)
Concrete (C)	BLS concrete ingredients (Commodity Code 132)	221.1 (1967 = 100)	71.6 (1982 = 100)	233.6 (1982 = 100)
Steel (D)	BLS steel mill products (Commodity Code 1017)	262.1 (1967 = 100)	75.0 (1982 = 100)	221.5 (1982 = 100)
Labor (E)	ENR skilled labor wage index	221.1 (1967 = 100)	2,467.8 (1913 = 100)	8,652.25 (1913 = 100)
Pipes and valves (F)	BLS valves and fittings (Commodity Code 114901; used Miscellaneous General Purpose Equipment 1149)	236.4 (1967 = 100)	70.2 (1982 = 100)	237.2 (1982 = 100)
Electrical and instrumentation (G)	BLS electrical machinery and equipment (Commodity Code 117)	167.5 (1967 = 100)	72.3 (1982 = 100)	113.3 (1982 = 100)
Housing (H)	ENR building cost index	254.8 (1967 = 100)	1,727.5 (1913 = 100)	5,027.59 (1913 = 100)
Maintenance material	BLS PPI for finished goods (Commodity Code SOP3000)	199.7 (1967 = 100)	71.6 (1982 = 100)	191.4 (1982 = 100)
Labor cost	ENR skilled labor wage		\$10/h	\$48.02/h
Electricity	Energy Information Administration		\$0.03/kW · h	\$0.1006/kW · h
Natural gas	Energy Information Administration		\$0.04590 m^3 (\$0.0013/scf)	\$0. 31677 m^3 (\$0.00897/scf)
Diesel	Energy Information Administration		\$0.1188/L (\$0.45/gal.)	\$1.020/L (\$3.863/gal.)

J. Infrastruct. Syst., 2013, 19(4): 451-464

Construction Cost Models

Generalized construction cost models were generated by performing regression analysis on the updated construction cost data. Microsoft Excel was used to generate the construction cost models. It was feasible to use Excel rather than more sophisticated statistical sofware because the number of data sets for each treatment unit was six at most. The selection of the appropriate model was made based on the maximum value of the coefficient of determination (R^2) among linear, exponential, polynomial, or power models.

Seventy-eight generalized construction cost models are presented in Table 2. Each model represented the construction cost of a treatment unit, which may be a part of the overall process train. The relevant ranges of each equation (minimum and maximum limits) and the percentage cost components are also provided. For example, the cost equation for rectangular clarifiers [Eq. (33)] has a relevant range of surface area from 22.29 to 445.9363 m^2 (240 to 4,800 ft^2).

The construction cost components are 4% excavation and site works (A); 25% manufactured equipment (B); 10% concrete (C); 26% steel (D); 23% labor (E); 11% piping and valves (F); and 1% electrical equipment and instrumentation (G). These percentages are based on average of 10 data points provided by Gumerman et al. (1979) and are illustrated in Fig. 1.

The generalized cost equations are shown in the following. For raw water pumping facilities

$$CC = 9{,}719.6x + 62{,}613 \quad (1)$$

$$CC = 13{,}060x + 71{,}118 \quad (2)$$

where CC = April 2011 construction cost and x = plant capacity (mgd). For pretreatment

$$CC = 3E - 6x^3 - 0.0158x^2 + 98.896x + 10{,}708 \quad (3)$$

$$CC = 0.0019x^2 + 14.58x + 498{,}011 \quad (4)$$

$$CC = 0.0022x^2 + 0.0563x + 438{,}275 \quad (5)$$

where x = chlorine feed capacity (lb/day). For chlorine dioxide generating and feed

$$CC = 2E - 5x^3 - 0.2x^2 + 794.67x + 83{,}312 \quad (6)$$

where x = chlorine dioxide feed capacity (lb/day). For ozone generation systems

$$CC = 0.0002x^3 - 1.5794x^2 + 4{,}424.4x + 214{,}180 \quad (7)$$

where x = ozone generation capacity (lb/day). For ozone contact chambers

$$CC = 6.3332x + 40{,}147 \quad (8)$$

where x = contact chamber volume (ft^3). For on-site hypochlorite generation systems

$$CC = 8E - 6x^3 - 0.147x^2 + 919.48x + 91{,}193 \quad (9)$$

where x = hypochlorite generation rate (lb/day). For powered activated carbon feed systems

$$CC = -0.0603x^2 + 814.58x + 182{,}000 \quad (10)$$

where x = feed capacity (lb/h). For powered carbon regeneration fluidized bed processes

$$CC = 7 \times 10^{-7}x^3 - 0.0375x^2 + 864.2x + 2{,}000{,}000 \quad (11)$$

where x = regeneration capacity (lb/day). For powered carbon regeneration atomized suspension processes

$$CC = 528.61x + 356{,}751 \quad (12)$$

where x = regeneration capacity (lb/day). For aeration

$$CC = -8.1678x^2 + 51{,}590x + 505{,}113 \quad (13)$$

where x = aeration basin volume [28.3168 m^3 (1,000 ft^3)]

$$CC = -20.581x^2 + 26{,}303x + 185{,}492 \quad (14)$$

where x = aeration tower volume [28.3168 m^3 (1,000 ft^3)]. For coagulation, precipitation, and flocculation

$$CC = -0.0262x^2 + 292.72x + 56{,}640 \quad (15)$$

$$CC = 251.52x + 74{,}291 \quad (16)$$

$$CC = -0.0022x^2 + 232.68x + 66{,}256 \quad (17)$$

$$CC = -0.0011x^2 + 186.38x + 66{,}300 \quad (18)$$

where x = feed capacity (lb/h)

$$CC = 0.191x^2 + 99.914x + 55{,}717 \quad (19)$$

where x = feed capacity (lb/day)

$$CC = -0.003x^2 + 50.198x + 23{,}490 \quad (20)$$

where x = feed capacity (gpd)

$$CC = 21.382x + 37{,}543 \quad (21)$$

where x = feed capacity (lb/day)

$$CC = 0.0002x^2 + 24.2x + 29{,}690 \quad (22)$$

$$CC = 0.0002x^2 + 30.862x + 31{,}569 \quad (23)$$

$$CC = 0.0002x^2 + 58.159x + 30{,}823 \quad (24)$$

$$CC = 4.8667x + 229{,}033 \quad (25)$$

$$CC = 5.7963x + 224{,}760 \quad (26)$$

$$CC = -5E - 6x^2 + 9.963x + 169{,}137 \quad (27)$$

$$CC = -0.0005Ex^2 + 28.571x + 36{,}347 \quad (28)$$

$$CC = -0.0006x^2 + 29.796x + 34{,}290 \quad (29)$$

$$CC = -0.0005x^2 + 29.031x + 35{,}457 \quad (30)$$

where x = total basin volume (ft^3). For sedimentation

$$CC = -0.0031x^2 + 140.98x + 221{,}973 \quad (31)$$

where x = net effective settling area (ft^2). For clarifiers

$$CC = -0.0006x^2 + 98.952x + 191{,}806 \quad (32)$$

$$CC = -0.0029x^2 + 169.19x + 94{,}365 \quad (33)$$

where x = surface area (ft^2). For tube settling modules

$$CC = 63.039x + 51{,}470 \quad (34)$$

J. Infrastruct. Syst., 2013, 19(4): 451-464

Table 2. Generalized Construction Cost Equations and Their Components

Unit operations and processes	Construction cost											
	Cost equation	Equation number	Percentage of component cost								Applicable range of x	
			A	B	C	D	E	F	G	H	Minimum	Maximum
Raw water pumping												
Raw water pumping facilities												
TDH = 9.144 m (30 ft)	$CC = 9719.6x + 62{,}613$	(1)		40			19	36	5		1	200
TDH = 30.48 m (100 ft)	$CC = 13060x + 71{,}118$	(2)		45			15	27	13		1	200
	x = plant capacity (mgd)											
Pretreatment												
Chlorine storage and feed												
Cylinder storage	$CC = 3E-6x^3 - 0.0158x^2 + 98.896x + 10{,}708$	(3)		40			6	4	2	48	10	10,000
On-site storage tank with rail delivery	$CC = 0.0019x^2 + 14.58x + 498{,}011$	(4)		79		2	10	4	3	2	2,000	10,000
Direct feed from rail car	$CC = 0.0022x^2 + 0.0563x + 438{,}275$	(5)		82			8	5	3	2	2,000	10,000
	x = chlorine feed capacity (lb/day)											
Chlorine dioxide generating and feed	$CC = 2E-5x^3 - 0.2x^2 + 794.67x + 83{,}312$	(6)		29			36	3	2	30	1	5,000
	x = chlorine dioxide feed capacity (lb/day)											
Ozone generation systems	$CC = 0.0002x^3 - 1.5794x^2 + 4{,}424.4x + 214{,}180$	(7)		78			19			3	10	3,500
	x = ozone generation capacity (lb/day)											
Ozone contact chambers	$CC = 6.3332x + 40{,}147$	(8)		6	19	28	47				460	92,000
	x = contact chamber volume (ft^3)											
On-site hypochlorite generation systems	$CC = 8E-6x^3 - 0.147x^2 + 919.48x + 91{,}193$	(9)		66			25	3	6		10	10,000
	x = hypochlorite generation rate (lb/day)											
Powdered activated carbon feed systems	$CC = -0.0603x^2 + 814.58x + 182{,}000$	(10)	1	55	4	6	8	14	10	2	3.5	7,000
	x = feed capacity (lb/h)											
Powdered carbon regeneration: fluidized bed process	$CC = 7E-7x^3 - 0.0375x^2 + 864.2x + 2{,}000{,}000$	(11)		49			42		8	1	209	33,360
	x = regeneration capacity (lb/day)											
Powdered carbon regeneration: atomized suspension process	$CC = 528.61x + 356{,}751$	(12)		85					7	8	1,000	10,000
	x = regeneration capacity (lb/day)											
Aeration												
Diffused aeration basin	$CC = -8.1678x^2 + 51{,}590x + 505{,}113$	(13)	1	63	2	2	21		9	2	1.9	380
	x = aeration basin volume [28.3168 m^3 (1,000 ft^3)]											
Aeration towers	$CC = -20.581x^2 + 26{,}303x + 185{,}492$	(14)		64	7	7	20		2		0.68	256
	x = aeration tower volume [28.3168 m^3 (1,000 ft^3)]											
Coagulation, precipitation, and flocculation												
Liquid alum feed system	$CC = -0.0262x^2 + 292.72x + 56{,}640$	(15)		63			14	3	4	16	5.4	5,400
Dry alum feed system	$CC = 251.52x + 74{,}291$	(16)		40			4	5	3	48	10	5,000
Ferrous sulfate feed systems	$CC = -0.0022x^2 + 232.68x + 66{,}256$	(17)		41			4	5	3	47	10.7	5,350
Ferric sulfate feed systems	$CC = -0.0011x^2 + 186.38x + 66{,}300$	(18)		41			4	5	3	47	13.3	6,600
	x = feed capacity (lb/h)											
Polymer feed systems	$CC = 0.191x^2 + 99.914x + 55{,}717$	(19)		70			4	2	4	20	1	200
	x = feed capacity (lb/day)											
Sulfuric acid feed systems	$CC = -0.003x^2 + 50.198x + 23{,}490$	(20)		59			20	8	6	7	10	5,000
	x = feed capacity (gpd)											
Sodium hydroxide feed systems	$CC = 21.382x + 37{,}543$	(21)		32			7	3	6	52	10	10,000
	x = feed capacity (lb/day)											
Rapid mix, G = 300/s	$CC = 0.0002x^2 + 24.2x + 29{,}690$	(22)	4	37	9	13	23		14		100	20,000
Rapid mix, G = 600/s	$CC = 0.0002x^2 + 30.862x + 31{,}569$	(23)	3	47	7	10	21		12		100	20,000
Rapid mix, G = 900/s	$CC = 0.0002x^2 + 58.159x + 30{,}823$	(24)	2	67	4	6	17		4		100	20,000

J. Infrastruct. Syst., 2013, 19(4): 451-464

Table 2. (*Continued.*)

	Construction cost											
			Percentage of component cost								Applicable range of x	
Unit operations and processes	Cost equation	Equation number	A	B	C	D	E	F	G	H	Minimum	Maximum
Horizontal paddle systems, G = 20/s	$CC = 4.8667x + 229{,}033$	(25)	6	17	16	21	30		10		1,800	1,000,000
Flocculation: horizontal paddle systems, G = 50/s	$CC = 5.7963x + 224{,}760$	(26)	5	24	14	19	29		9		1,800	1,000,000
Horizontal paddle systems, G = 80/s	$CC = -5E - 6x^2 + 9.963x + 169{,}137$	(27)	4	34	11	14	30		7		1,800	500,000
Vertical turbine flocculators, G = 20/s	$CC = -0.0005Ex^2 + 28.571x + 36{,}347$	(28)	3	21	11	15	35		15		1,800	25,000
Vertical turbine flocculators, G = 50/s	$CC = -0.0006x^2 + 29.796x + 34{,}290$	(29)	3	22	10	15	34		15		1,800	25,000
Vertical turbine flocculators, G = 80/s	$CC = -0.0005x^2 + 29.031x + 35{,}457$	(30)	3	23	10	15	34		15		1,800	25,000
	x = total basin volume (ft^3)											
Sedimentation												
Upflow solid contact clarifiers	$CC = -0.0031x^2 + 140.98x + 221{,}973$	(31)	5	48	8	10	28		1		255	14,544
	x = net effective settling area (ft^2)											
Circular clarifiers	$CC = -0.0006x^2 + 98.952x + 191{,}806$	(32)	3	29	8	38	15	6	1		707	31,416
Rectangular clarifiers	$CC = -0.0029x^2 + 169.19x + 94{,}365$	(33)	4	25	10	26	23	11	1		240	4,800
	x = surface area (ft^2)											
Tube settling modules	$CC = 63.039x + 51{,}470$	(34)		48		29	23				1	200
	x = tube module area (ft^2)											
Contact basins	$CC = 674.24x^{0.5804}$	(35)	8		20	30	42				2,640	52,800
	x = basin volume (ft^2)											
Filtration												
Gravity filtration structures	$CC = 0.000001x^3 - 0.0439x^2 + 1{,}039x + 477{,}982$	(36)	1	18	6	4	24	26	3	18	140	28,000
	x = total filter area (ft^2)											
Filtration media												
Rapid sand	$CC = 7827.9x + 13{,}969$	(37)		100							1	200
Dual media	$CC = 5986x + 21{,}241$	(38)		100							1	200
Mixed media	$CC = 9770.8x + 26{,}400$	(39)		100							1	200
	x = plant flow rate (mgd)											
Capping sand filters with anthracite	$CC = 9.6641x + 1{,}844$	(40)		39			61				350	70,000
	x = filter area (ft^2)											
Modification of rapid sand filters to high rate filters	$CC = -0.0004x^2 + 70.703x + 85{,}920$	(41)					38	56	6		140	28,000
	x = total filter area (ft^2)											
Backwash pumping facilities	$CC = 12.427x^3 - 650.05x^2 + 23{,}879x + 69{,}478$	(42)		49			9	30	12		1.8	33.0
	x = pumping capacity (gpm)											
Hydraulic surface wash systems	$CC = 0.0006x^2 + 50.64x + 80{,}743$	(43)		62			13	13	12		140	28,000
	x = total filter area (ft^2)											
Air-water backwash facilities	$CC = -0.0003x^2 + 71.761x + 259{,}609$	(44)		31			11	53	5		140	28,000
	x = total filter area (ft^2)											
Wash water surge basins	$CC = 869.07x^{0.5845}$	(45)	1		32	15	46	5	1		10,000	500,000
	x = basin capacity (gal.)											
Wash water storage tanks	$CC = 886.95x + 27{,}291$	(46)	2		1	40	57				21	900
	x = storage volume [3,785.41 L (1,000 gal.)]											
Continuous automatic backwash filter	$CC = 222{,}371x + 327{,}217$	(47)	1	47	8	3	14	1	2	24	1	200
	x = plant flow (mgd)											
Pressure filtration plants	$CC = 163{,}104x + 280{,}848$	(48)		47			9	29	7	8	1	200
	x = plant flow (mgd)											

Table 2. (*Continued.*)

Unit operations and processes	Construction cost: Cost equation	Equation number	Percentage of component cost: A	B	C	D	E	F	G	H	Applicable range of x: Minimum	Maximum
Taste and odor control												
Potassium permanganate feed systems	$CC = -0.0578x^2 + 60.011x + 23{,}874$	(49)		37			8	13	20	22	1	500
	x = feed capacity (lb/day)											
Disinfection												
Anhydrous ammonia feed facilities	$CC = 1E-5x^3 - 0.0788x^2 + 212.21x + 38{,}691$	(50)		55			18	12	6	9	250	5,000
	x = feed capacity (lb/day)											
Aqua ammonia feed facilities	$CC = 1E-6x^3 - 0.0094x^2 + 40.444x + 26{,}000$	(51)		76			7	7	10		250	5,000
	x = feed capacity (lb/day)											
Reverse osmosis	$CC = -0.0007x^2 + 1246.6x + 2{,}000{,}000$	(52)		81			6		6	7	1	200
	x = plant capacity [3,785.41 lpd (1,000 gpd)]											
Ion exchange												
Pressure ion exchange softening	$CC = -179.5x^2 + 294{,}490x + 40{,}635$	(53)		52		1	12	17	10	8	1.1	122.6
Gravity ion exchange softening	$CC = -129.08x^2 + 172{,}384x + 468{,}494$	(54)	1	67	3	3	9	8	2	7	1.5	150
Pressure ion exchange nitrate removal	$CC = 238.05x^2 + 456{,}696x + 182{,}502$	(55)		71	1	1	8	9	4	5	1.1	12.3
	x = plant capacity (mgd)											
Fluoride removal												
Activated alumina for fluoride removal	$CC = 60.886x^2 + 192{,}706x + 107{,}664$	(56)		51			17	20	2	10	0.7	135
	x = plant capacity (mgd)											
Stability												
Lime feed systems	$CC = 55{,}908 \ln(x) - 61{,}281$	(57)		65			3	6	5	22	10	1,000
	$CC = 20.872x + 200{,}332$	(58)		67			3	6	5	19	1,000	10,000
	x = lime feed capacity (lb/h)											
Recarbonation basin	$CC = 4E-9x^3 - 0.0002x^2 + 11.012x + 21{,}230$	(59)	7		20	29	41	3			770	35,200
	x = single basin volume (ft^3)											
Recarbonation: submerged burners as CO_2 source	$CC = -0.0006x^2 + 23.786x + 145{,}970$	(60)		55			25	17		3	500	10,000
	x = installed capacity (lb/day)											
Recarbonation: stack gas as CO_2 source	$CC = 1546.8x^{0.5399}$	(61)		46			31	15	8		2,500	50,000
	x = installed capacity (lb/CO_2/day)											
Granular carbon regeneration: fluid bed process	$CC = -0.001x^2 + 86.917x + 2{,}000{,}000$	(62)		66			25		1	8	6,000	24,000
	x = regeneration capacity (lb/day)											
Clear water storage and distribution												
Below-ground clearwell storage	$CC = -0.0782x^2 + 1{,}271.1x + 118{,}926$	(63)	3		43	19	34		1		10	7,500
	x = clearwell capacity [3,785.41 L (1,000 gal.)]											
Ground-level clearwell storage	$CC = -0.0104x^2 + 438.09x + 127{,}452$	(64)		76	10	5	2	6	1		8.5	9,400.4
	x = clearwell capacity [3,785.41 L (1,000 gal.)]											
Finished water pumping facilities												
TDH = 9.144 m (30 ft)	$CC = -5.0351x^2 + 13{,}443x + 46{,}141$	(65)		44			13	28	15		1.5	300
TDH = 30.48 m (100 ft)	$CC = 0.9446x^2 + 19{,}736x + 118{,}832$	(66)		60			10	17	13		1.5	300
	x = plant capacity (mgd)											
In-plant pumping	$CC = 12.288x^2 + 12{,}980x + 89{,}161$	(67)		17	2	3	38	28	6	6	1	200
	x = plant flow (mgd)											

Table 2. (*Continued.*)

Unit operations and processes	Construction cost: Cost equation	Equation number	A	B	C	D	E	F	G	H	Applicable range of x: Minimum	Maximum
Residual processing and disposal												
Chemical sludge pumping: unthickened sludge	$CC = 2E-6x^3 - 0.0258x^2 + 183.11x + 94{,}222$ x = pumping capacity (gpm)	(68)	1	15	6	5	31	30	5	7	20	10,000
Chemical sludge pumping: thickened sludge	$CC = 0.0004x^3 - 0.7701x^2 + 514.05x + 22{,}988$ x = pumping capacity (gpm)	(69)		67			17	4	3	9	5	1,250
Gravity sludge thickeners	$CC = 0.3083x^3 - 67.967x^2 + 9{,}765.2x - 16{,}364$ x = diameter (ft)	(70)	4	38	12	15	30		1		20	150
Vacuum filters	$CC = -0.1735x^2 + 1940x + 486{,}864$ x = total filter area (ft^2)	(71)		50			26	2	1	21	9.4	1,320
Sludge dewatering lagoons	$CC = 16.844x^3 - 1{,}557.5x^2 + 63{,}756x + 14{,}724$ x = effective storage volume (million gal.)	(72)	54		4		26	16			0.3	60
Filter press	$CC = 0.0097x^3 - 12.997x^2 + 10{,}010x + 766{,}194$ x = total filter press volume (ft^3)	(73)		61			22	1		16	4.3	896
Decanter centrifuges	$CC = 0.014x^3 - 13.264x^2 + 5{,}877.1x + 429{,}507$ x = machine capacity (gpm)	(74)		50			19	7	1	23	10	500
Basket centrifuges	$CC = -0.0075x^3 + 8.4058x^2 + 4{,}270.7x + 484{,}659$ x = total machine capacity [3,785.41 lpd (1,000 gpd)]	(75)		52			20	4	1	23	3.6	720
Sand drying beds	$CC = -10.47x^2 + 11{,}308x + 15{,}471$ x = total bed area capacity [92.903 m^2 (1,000 ft^2)]	(76)	5		10	2	58	25			5	400
Belt filter press	$CC = -2.2562x^2 + 22{,}279x + 242{,}323$ x = total installed machine capacity (gpm)	(77)		65			24	3		8	15	450
Management												
Administrative, laboratory, and maintenance building	$CC = 73024x^{0.5523}$ x = plant capacity (mgd)	(78)								100	1	200

Note: A = excavation and site work; B = manufactured equipment; C = concrete; D = steel; E = labor; F = pipes and valaves; G = electrical and instrumentation; H = housing; CC = April 2011 construction cost; TDH = total dynamic head.

J. Infrastruct. Syst., 2013, 19(4): 451-464

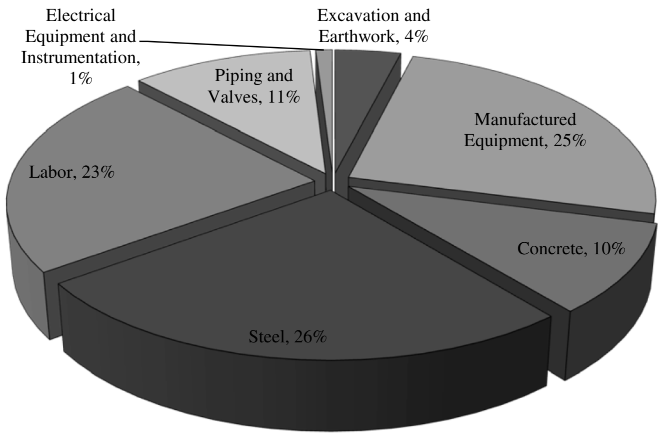

Fig. 1. Percentages of different cost components for rectangular clarifiers

where x = tube module area (ft^2). For contact basins

$$CC = 674.24x^{0.5804} \tag{35}$$

where x = basin volume (ft^2). For filtration

$$CC = 0.000001x^3 - 0.0439x^2 + 1{,}039x + 477{,}982 \tag{36}$$

where x = total filter area (ft^2). For filtration media

$$CC = 7{,}827.9x + 13{,}969 \tag{37}$$

$$CC = 5{,}986x + 21{,}241 \tag{38}$$

$$CC = 9{,}770.8x + 26{,}400 \tag{39}$$

where x = plant flow rate (mgd). For capping sand filters with anthracite

$$CC = 9.664x + 1{,}844 \tag{40}$$

where x = filter area (ft^2). For modification of rapid sand filters to high rate filters

$$CC = -0.0004x^2 + 70.703x + 85{,}920 \tag{41}$$

where x = total filter area (ft^2). For backwash pumping facilities

$$CC = 12.427x^3 - 650.05x^2 + 23{,}879x + 69{,}478 \tag{42}$$

where x = pumping capacity (gpm). For hydraulic surface wash systems and air-water backwash facilities

$$CC = 0.0006x^2 + 50.64x + 80{,}743 \tag{43}$$

$$CC = -0.0003x^2 + 71.761x + 259{,}609 \tag{44}$$

where x = total filter area (ft^2). For wash water surge basins

$$CC = 869.0x^{0.5845} \tag{45}$$

where x = basin capacity (gal.). For wash water storage tanks

$$CC = 886.95x + 27{,}291 \tag{46}$$

where x = storage volume [3,785.41 L (1,000 gal.)]. For continuous automatic backwash filters

$$CC = 222{,}371x + 327{,}217 \tag{47}$$

where x = plant flow (mgd). For pressure filtration plants

$$CC = 163{,}104x + 280{,}848 \tag{48}$$

where x = plant flow (mgd). For taste and odor control

$$CC = -0.0578x^2 + 60.011x + 23{,}874 \tag{49}$$

where x = feed capacity (lb/day). For disinfection

$$CC = 1E-5x^3 - 0.0788x^2 + 212.21x + 38{,}691 \tag{50}$$

$$CC = 1E-6x^3 - 0.0094x^2 + 40.444x + 26{,}000 \tag{51}$$

where x = feed capacity (lb/day). For reverse osmosis

$$CC = -0.0007x^2 + 1246.6x + 2{,}000{,}000 \tag{52}$$

where x = plant capacity [3,785.41 lpd (1,000 gpd)]. For ion exchange

$$CC = -179.5x^2 + 294{,}490x + 40{,}635 \tag{53}$$

$$CC = -129.08x^2 + 172{,}384x + 468{,}494 \tag{54}$$

$$CC = 238.05x^2 + 456{,}696x + 182{,}502 \tag{55}$$

where x = plant capacity (mgd). For fluoride removal

$$CC = 60.886x^2 + 192{,}706x + 107{,}664 \tag{56}$$

where x = plant capacity (mgd). For stability

$$CC = 55{,}908\ln(x) - 61{,}281 \tag{57}$$

$$CC = 20.872x + 200{,}332 \tag{58}$$

where x = lime feed capacity (lb/h). For recarbonation basins

$$CC = 4E-9x^3 - 0.0002x^2 + 11.012x + 21{,}230 \tag{59}$$

where x = single basin volume (ft^3). For recarbonation with submerged burners as a CO_2 source

$$CC = -0.0006x^2 + 23.786x + 145{,}970 \tag{60}$$

where x = installed capacity (lb/day). For recarbonation with stack gas as a CO_2 source

$$CC = 1{,}546.8x^{0.5399} \tag{61}$$

where x = installed capacity (lb/CO_2/day). For granular carbon regeneration as a fluid bed process

$$CC = -0.001x^2 + 86.917x + 2{,}000{,}000 \tag{62}$$

where x = regeneration capacity (lb/day). For clear water storage and distribution

$$CC = -0.0782x^2 + 1{,}271.1x + 118{,}926 \tag{63}$$

$$CC = -0.0104x^2 + 438.09x + 127{,}452 \tag{64}$$

where x = clearwell capacity [3,785.41 L (1,000 gal.)]. For finished water pumping facilities

$$CC = -5.0351x^2 + 13{,}443x + 46{,}141 \tag{65}$$

J. Infrastruct. Syst., 2013, 19(4): 451-464

$$CC = 0.9446x^2 + 19{,}736x + 118{,}832 \quad (66)$$

where x = plant capacity (mgd). For in-plant pumping

$$CC = 12.288x^2 + 12{,}980x + 89{,}161 \quad (67)$$

where x = plant flow (mgd). For processing and disposal of residuals

$$CC = 2E - 6x^3 - 0.0258x^2 + 183.11x + 94{,}222 \quad (68)$$

$$CC = 0.0004x^3 - 0.7701x^2 + 514.05x + 22{,}988 \quad (69)$$

where x = pumping capacity (gpm). For gravity sludge thickeners

$$CC = 0.3083x^3 - 67.967x^2 + 9{,}765.2x - 16{,}364 \quad (70)$$

where x = diameter (ft). For vacuum filters

$$CC = -0.1735x^2 + 1{,}940x + 486{,}864 \quad (71)$$

where x = total filter area (ft^2). For sludge dewatering lagoons

$$CC = 16.844x^3 - 1{,}557.5x^2 + 63{,}756x + 14{,}724 \quad (72)$$

where x = effective storage volume (million gal.). For filter presses

$$CC = 0.0097x^3 - 12.997x^2 + 10{,}010x + 766{,}194 \quad (73)$$

where x = total filter press volume (ft^3). For decanter centrifuges

$$CC = 0.014x^3 - 13.264x^2 + 5{,}877.1x + 429{,}507 \quad (74)$$

where x = machine capacity (gpm). For basket centrifuges

$$CC = -0.0075x^3 + 8.4058x^2 + 4{,}270.7x + 484{,}659 \quad (75)$$

where x = total machine capacity [3,785.41 lpd (1,000 gpd)]. For sand drying beds

$$CC = -10.47x^2 + 11{,}308x + 15{,}471 \quad (76)$$

where x = total bed area capacity [$92.903\ m^2$ ($1{,}000\ ft^2$)]. For bed filter presses

$$CC = -2.2562x^2 + 22{,}279x + 242{,}323 \quad (77)$$

where x = total installed machine capacity (gpm). For management

$$CC = 73024x^{0.5523} \quad (78)$$

where x = plant capacity (mgd).

Update of Construction Costs

Gumerman et al. (1979) recommended two methods to apply indexes to update the construction cost for a given time. The first method is to apply a single index to update the total construction cost, and the second method is to use different indexes for eight aggregated cost components. Although it is simple, use of a single index is often inadequate for applications to water utility construction (Qasim et al. 1992). The second method uses multiple cost indexes, but gives a more accurate cost update as a result of different indexes.

The results obtained through construction cost updating by these two methods may vary greatly, depending upon the time interval involved. If the time is short, the updated construction costs from both methods are close. On the other hand, for a long time interval (such as more than eight years), the construction costs updated for the same treatment unit using either of these methods may vary greatly as a result of large variations in cost factors within eight aggregated cost components. Examples of such variations in estimated costs using single and multiple indexes over time were presented by Sharma (2010). For this reason, the construction cost models (Table 2) were developed for April 2011 construction costs for treatment units by using multiple indexes. Further updates of the construction costs are from April 2011, and the use of a single index will provide approximately the same construction cost update as the use of multiple indexes. However, it is recommended that every eight years, the cost equations are revised by using the multiple BLS and ENR indexes for applicable cost components (Sharma 2010). Cost components as a percentage of total April 2011 costs are included in Table 2. These percentages can be used for multiple indexes if further updates are desired.

The procedure of updating the estimated construction cost is simple. The most recent index value of ENR index is obtained from latest issue of ENR or the ENR website. The index value thus obtained is divided by the April 2011 index value (with the same base year as that of most recent index) to obtain a factor for the cost update. The April 2011 construction cost is multiplied by that factor to obtain the current construction cost. Eq. (79) presents the current construction cost.

$$\begin{aligned} CCC &= \text{April 2011 CC} \\ &\quad \times (\text{current ENR index}/\text{April 2011 ENR index}) \end{aligned} \quad (79)$$

where CCC = current construction cost.

Generalized Annual O&M Costs

The generalized October 1978 annual O&M costs for water treatment units were obtained from Gumerman et al. (1979). These generalized O&M costs include cost for energy (electricity, natural gas, and diesel), labor, and maintenance materials. The 1979 estimates were based on unit energy cost of \$0.03 $kW \cdot h$ for electricity, \$0.04590 m^3 (\$0.0013/scf) for natural gas, and \$0.1188/L (\$0.45 gal.) for diesel. Unit labor costs were based on \$10 labor/h. Maintenance material costs, however, did not include the cost of chemicals required for the operation of treatment unit. The costs of chemicals must be added separately, as shown later. October 1978 O&M costs data were updated to April 2011. The updated energy costs are: electricity, \$0.1006 $kW \cdot h$ (Energy Information Administration 2011a); natural gas, \$0. 31677 m^3.(\$0.00897/scf) (Energy Information Administration 2011b); and diesel, \$1.020/L (\$3.863 gal.) (Energy Information Administration 2011c). Likewise, the updated April 2011 labor costs of \$48.02labor/h (Engineering News Record 2011) were used. In these calculations, the October 1978 maintenance material costs were updated to April 2011 maintenance material costs by using the BLS PPI for finished goods (Commodity Code SOP3000), which is 191.4.

O&M Cost Models

The generalized O&M cost models were also developed with regression by using Excel. The updated April 2011 O&M cost data were used to generate O&M cost equations. Sixty-three generalized O&M cost equations are given in Table 3. The applicable range of the equations and the percentages of total annual O&M costs for each of three cost components (energy, labor, and maintenance

J. Infrastruct. Syst., 2013, 19(4): 451-464

Table 3. Generalized O&M Cost Equations and Their Components

Process	Operation and maintenance cost								
			Percentage of component cost					Applicable range of x	
	Cost equation	Equation	I	J	K	L	M	Minimum	Maximum
Raw water pumping									
Raw water pumping facilities									
TDH = 9.144 m (30 ft)	O & MC $= 5{,}962.8x + 24{,}960$	(80)	72			22	6	1	200
TDH = 30.48 m (100 ft)	O & MC $= 8{,}979.1x + 24{,}960$	(81)	81			15	4	1	200
	x = plant capacity (mgd)								
Pretreatment									
Chlorine storage and feed									
Cylinder storage	O & MC $= 6\text{E}-07x^3 - 0.009x^2 + 68.236x + 21{,}371$	(82)	18			74	8	10	10,000
On-site storage tank with rail delivery	O & MC $= -0.0003x^2 + 6.134x + 46{,}618$	(83)	2			74	24	2,000	10,000
Direct feed from rail car	O & MC $= -0.00006x^2 + 2.3116x + 45{,}082$	(84)	3			67	30	2,000	10,000
	x = chlorine feed capacity (lb/day)								
Chlorine dioxide generation and feed	O & MC $= -0.0112x^2 + 111.32x + 34{,}196$	(85)	6			85	9	1	5,000
	x = chlorine dioxide feed capacity (lb/day)								
Ozone generation systems	O & MC $= -0.01x^2 + 367.19x + 35{,}653$	(86)	76			16	8	10	3,500
	x = ozone generation capacity (lb/day)								
On-site hypochlorite generation systems	O & MC $= -0.0017x^2 + 147.84x + 29{,}106$	(87)	66			20	14	10	10,000
	x = hypochlorite generation rate (lb/day)								
Powdered activated carbon feed systems	O & MC $= -0.0212x^2 + 273.89x + 57{,}086$	(88)	26			56	18	3.5	7,000
	x = feed capacity (lb/h)								
Powdered carbon regeneration: fluidized bed process	O & MC $= 0.00003x^2 + 53.034x + 85{,}538$	(89)	42	43		14	1	220	32,570
	x = regeneration capacity (lb/day)								
Powdered carbon regeneration: atomized suspension process	O & MC $= 56.254x + 56{,}588$	(90)	7	75		16	2	1,000	10,000
	x = regeneration capacity (lb/day)								
Aeration									
Diffused aeration basin	O & MC $= 20{,}172x + 81{,}077$	(91)	73			26	1	1.9	380
	x = aeration basin volume [28.3168 m^3 (1,000 ft^3)]								
Aeration towers	O & MC $= 1{,}588.8x + 4{,}574$	(92)[28.3168 m^3 (1,000 ft^3)]	62			22	16	0.68	256
	x = aeration tower volume [28.3168 m^3 (1,000 ft^3)]								
Coagulation, precipitation, and flocculation									
Liquid alum feed system	O & MC $= 2{,}212.7x^{0.2919}$	(93)	51			46	3	5.4	5,400
Dry alum feed system	O & MC $= 0.0004x^2 + 46.611x + 14{,}841$	(94)	12			86	2	10	5,000
Ferrous sulfate feed systems	O & MC $= 45.684x + 14{,}195$	(95)	12			86	2	10.7	5,350
Ferric sulfate feed systems	O & MC $= 37.043x + 14{,}070$	(96)	12			86	2	13.3	6,660
	x = feed capacity (lb/h)								
Polymer feed systems	O & MC $= 0.0194x^2 + 8.5881x + 12{,}771$	(97)	19			74	7	1	200
	x = feed capacity (lb/day)								
Sulfuric acid feed systems	O & MC $= 4.8993x + 5{,}778$	(98)	4			94	2	10	5,000
	x = feed capacity (gpd)								
Sodium hydroxide feed systems	O & MC $= 0.0002x^2 - 0.9146x + 6{,}980$	(99)	28			69	3	10	10,000
	x = feed capacity (lb/day)								
Rapid mix, G = 300	O & MC $= -3\text{E}-08x^3 + 0.0008x^2 + 2.8628x + 23{,}676$	(100)	44			55	1	100	20,000
Rapid mix, G = 600	O & MC $= -3\text{E}-08x^3 + 0.0008x^2 + 7.9834x + 23{,}676$	(101)	61			38	1	100	20,000
Rapid mix, G = 900	O & MC $= 37.081x + 18{,}839$	(102)	84			16		100	20,000
Flocculation: horizontal paddle systems, G = 20	O & MC $= 3\text{E}-13x^3 - 5\text{E}-07x^2 + 0.2937x + 6{,}963$	(103)	11			41	48	1,800	1,000,000

J. Infrastruct. Syst., 2013, 19(4): 451-464

Table 3. (*Continued.*)

Process	Operation and maintenance cost: Cost equation	Equation	Percentage of component cost: I	J	K	L	M	Applicable range of x: Minimum	Maximum
Flocculation: horizontal paddle systems, G = 50	O & MC = $3E-13x^3-5E-07x^2+0.3935x+6{,}960$	(104)	44			30	26	1,800	1,000,000
Flocculation: horizontal paddle systems, G = 80	O & MC = $-3E-07x^2+0.5942x+7{,}126$	(105)	64			20	16	1,800	500,000
	x = total basin volume (ft^3)								
Sedimentation									
Upflow solid contact clarifiers	O & MC = $-0.00007x^2+3.8893x+25{,}236$	(106)	24			67	9	20	150
	x = net effective settling area (ft^2)								
Circular clarifiers, lime sludge	O & MC = $8E-10x^3-0.00005x^2+1.6945x+7{,}207$	(107)	4			72	24	30	200
	x = surface area (ft^2)								
Circular clarifiers, ferric and alum sludge	O & MC = $8E-10x^3-0.00005x^2+1.6826x+7{,}065$	(108)	3			73	24	30	200
	x = surface area (ft^2)								
Rectangular clarifiers	O & MC = $4.2948x+8{,}283$	(109)	3			89	8	240	4,800
	x = surface area (ft^2)								
Filtration									
Gravity filtration structures	O & MC = $7E-8x^3-0.0026x^2+61.589x+49{,}584$	(110)	30			62	8	1	200
	x = plant flow rate (mgd)								
Backwash pumping facilities	O & MC = $3E-09x^3-0.0002x^2+5.1398x+11{,}540$	(111)	50			32	18	140	28,000
	x = pumping capacity (gpm)								
Hydraulic surface wash systems	O & MC = $4E-09x^3-0.0002x^2+3.9838x+4{,}682$	(112)	43			54	3	140	28,000
	x = total filter area (ft^2)								
Air-water backwash facilities	O & MC = $3E-09x^3-0.0002x^2+5.1705x+11{,}540$	(113)	50			18	32	140	28,000
	x = total filter area (ft^2)								
Continuous automatic backwash filter	O & MC = $-4.5602x^2+14{,}524x+7{,}972$	(114)	63			33	4	1	200
	x = plant flow (mgd)								
Pressure filtration plants	O & MC = $0.2664x^3-85.823x^2+17{,}002x+69{,}995$	(115)	41			49	10	1	200
	x = plant flow (mgd)								
Taste and odor control									
Potassium permanganate feed systems	O & MC = $2{,}976.2\ln(x)+9{,}007$	(116)	4			95	1	1	500
	x = feed capacity (lb/day)								
Disinfection									
Anhydrous ammonia feed facilities	O & MC = $7E-07x^3-0.0061x^2+21.997x+28{,}333$	(117)	5			67	28	250	5,000
Aqua ammonia feed facilities	O & MC = $2E-08x^3-0.0002x^2+0.8031x+7{,}451$	(118)	1			89	10	250	5,000
	x = feed capacity (lb/day)								
Reverse osmosis	O & MC = $414{,}135x+222{,}705$	(119)	55			1	44	1	200
	x = plant capacity (mgd)								
Ion exchange									
Pressure ion exchange softening	O & MC = $-12.508x^2+20{,}266x+107{,}156$	(120)	14			35	51	1.1	122.6
Gravity ion exchange softening	O & MC = $17{,}212x+113{,}894$	(121)	8			36	56	1.5	150
	x = plant flow rate (mgd)								
Pressure ion exchange nitrate removal	O & MC = $-549.12x^2+76{,}275x+94{,}285$	(122)	4			26	70	1.1	12.3
	x = plant capacity (mgd)								
Fluoride removal									
Activated alumina for fluoride removal	O & MC = $12{,}991x+102{,}149$	(123)	12			51	37	0.7	135
	x = plant capacity (mgd)								

J. Infrastruct. Syst., 2013, 19(4): 451-464

Table 3. (*Continued.*)

Process	Operation and maintenance cost: Cost equation	Equation	Percentage of component cost: I	J	K	L	M	Applicable range of x: Minimum	Maximum
Stability									
Lime feed systems	O & MC $= 4{,}826.1x^{0.4593}$ x = feed capacity (lb/day)	(124)	4			93	3	10	10,000
Recarbonation: submerged burners as CO_2 source	O & MC $= 31.649x + 14{,}114$ x = installed capacity (lb/day)	(125)	13	81		4	2	500	10,000
Recarbonation: stack gas as CO_2 source	O & MC $= -0.00001x^2 + 3.3038x + 6{,}902$ x = installed capacity (lb/CO_2/day)	(126)	54			27	19	2,500	50,000
Granular carbon regeneration: fluid bed process	O & MC $= 15.737x + 136{,}553$ x = regeneration capacity (lb/day)	(127)	9	41		37	13	6,000	24,000
Clear water storage and distribution									
Finished water pumping facilities									
TDH = 9.144 m (30 ft)	O & MC $= 6{,}504.9x + 23{,}488$	(128)	75			20	5	1.5	300
TDH = 30.48 m (100 ft)	O & MC $= 16{,}555x + 23{,}488$ x = plant capacity (mgd)	(129)	90			8	2	1.5	300
In-plant pumping									
TDH = 10.66 m (35 ft)	O & MC $= 6{,}719.5x + 24{,}739$	(130)	74			21	5	1	200
TDH = 22.86 m (75 ft)	O & MC $= 12{,}751x + 24{,}739$ x = pumping rate (mgd)	(131)	86			11	3	1	200
Residual processing and disposal									
Chemical sludge pumping: unthickened sludge	O & MC $= 4E-07x^3 - 0.0058x^2 + 43.748x + 11{,}622$ x = pumping rate (gpm)	(132)	25			27	48	20	10,000
Chemical sludge pumping: thickened sludge	O & MC $= -0.0467x^2 + 124x + 6{,}941$ x = pumping rate (gpm)	(133)	42			33	25	5	1,250
Gravity sludge thickeners	O & MC $= 0.4465x^2 + 89.895x + 4{,}751$ x = diameter (ft)	(134)	9			73	18	20	150
Vacuum filters	O & MC $= 0.0007x^3 - 1.5412x^2 + 1{,}524.6x + 50{,}695$ x = total filter area (ft^2)	(135)	26			53	21	9.4	1,320
Sludge dewatering lagoons	O & MC $= -0.0118x^2 + 379.89x + 5{,}233$ x = volume of sludge removed [28.3168 m^3 (1,000 ft^3)]	(136)			10	89	1	10	5,000
Filter press	O & MC $= -0.0022x^3 + 3.449x^2 + 353.95x + 370{,}550$ x = total filter press volume (ft^3)	(137)	10			88	2	4.3	896
Decanter centrifuges	O & MC $= 20{,}771x^{0.417}$ x = feed sludge flow (gpm)	(138)	27			61	12	10	500
Basket centrifuges	O & MC $= 1{,}097.2x + 27{,}965$ x = sludge flow rate [3,785.41 lpd (1,000 gpd)]	(139)	57			35	8	3.6	720
Sand drying beds	O & MC $= 0.7198x^2 + 1{,}883.8x + 25{,}400$ x = total sand drying bed area [92.903 m^2 (1,000 ft^2)]	(140)			10	86	4	5	400
Belt filter press	O & MC $= 0.6219x^2 + 1{,}673.7x + 50{,}156$ x = feed sludge flow rate (gpm)	(141)	30			62	8	15	450
Management									
Administrative, laboratory, and maintenance building	O & MC $= 92{,}981x^{0.4526}$ x = plant capacity (mgd)	3.63	10			85	5	1	200

Note: I = electricity Cost at \$0.1006/kW · h; J = natural gas cost at \$0. 31677 m^3.(\$0.00897/scf); K = diesel cost at \$1.020/L (\$3.863/gal.); L = labor cost at \$48.02/h; M = maintenance material cost.

material) are also provided in Table 3. The energy component includes electricity, natural gas, and diesel costs.

Update of O&M Cost Estimates

Updating O&M costs is accomplished from three individual components: (1) energy (to include electricity, natural gas, or diesel); (2) labor; and (3) maintenance materials. Energy and labor costs are updated by multiplying April 2011 component costs by a multiplication factor. This multiplication factor is obtained by dividing current unit costs by their April 2011 unit costs, mentioned previously. Gumerman et al. (1979) recommended use of the BLS PPI for finished goods (Commodity Code SOP3000) to update maintenance material costs. The O&M costs, which include maintenance material costs, are already updated to April 2011 costs in the equations given in Table 3. Therefore, if a short time interval is involved, the use of a single ENR index will yield results close to those obtained from the BLS index. However, for a long time interval (over eight years), the BLS index must be used.

Evaluation of Alternative Process Trains

The present worth (PW) of annual operation and maintenance costs is a sum that must be invested today at a given interest rate to pay for O&M costs every year throughout the life of the treatment plant. The PW of the annual O&M cost when added to the construction cost gives the PW of the project. The PW of the project can be used to calculate the equivalent annual cost of the project. The equivalent annual cost is a uniform series of expenditures at the end of each year that is equivalent to different nonuniform construction and O&M expenditures made during the life cycle of the treatment plant. The equivalent annual cost is used to calculate the cost per unit of treated water. Also, when different alternatives are considered, equivalent annual costs are used to compare and select the most cost-effective alternative.

Illustration

An example of a rectangular clarifier is given in the following to illustrate the procedure for developing preliminary construction and O&M costs, the present worth of O&M costs, and equivalent annual worth. The clarifier is designed to remove alum coagulated sludge. The design capacity of the clarifier is 1.314 m^3/s (30 mgd) and average flow is 0.670 m^3/s (15.3 mgd). These costs are developed for February 2013. The clarifier design and O&M data are summarized as follows: hydraulic loading on clarifier = $3,255.45\ \mathrm{lpd/ft^2}$ ($860\ \mathrm{gpd/ft^2}$); optimum liquid alum dose = 20 mg/L; liquid alum unit cost = \$0.44/kg (\$0.20 per lb); design life of treatment process = 20 years; interest rate = 6%; miscellaneous costs for special siteworks, overhead and profit, administration and interest during construction = 28% of total construcation cost.

1. Calculate surface area of clarifier. Total surface area of rectangular clarifier required = $3,242.32\ \mathrm{m}^2$ ($34,900\ \mathrm{ft}^2$) (30,000,000/860). The maximum limit of the CC equation for a rectangular clarifier is $445.93\ \mathrm{m}^2$ ($4,800\ \mathrm{ft}^2$). Eight rectangular clarifiers of $408.77\ \mathrm{m}^2$ ($4,400\ \mathrm{ft}^2$) surface area each will be required.
2. Calculate required liquid alum feed capacity. Design capacity of liquid alum feed system = 94.80 kg/h (209 lb/h) $(30 \times 20 \times 8.34/24)$.
3. Calculate April 2011 construction cost of clarifier [Eq. (33)]. $\mathrm{CC} = -0.0029x^2 + 169.19x + 94{,}365$. For $x = 408.77\ \mathrm{m}^2$ ($x = 4{,}400\ \mathrm{ft}^2$), CC = \$782,660. Construction cost of eight rectangular clarifiers = \$6,261,280.
4. Calculate April 2011 construction cost of liquid alum feed system [Eq. (15)]. $\mathrm{CC} = -0.0262x^2 + 292.72x + 56{,}640$. For $x = 94.80$ kg/h ($x = 209$ lb/h), CC = \$116,670.
5. Calculate April 2011 O&M cost of rectangular clarifier [Eq. (109)]. $\mathrm{O\ \&\ MC} = 4.2948x + 8{,}283$. For $x = 408.77\ \mathrm{m}^2$ ($x = 4{,}400\ \mathrm{ft}^2$), O & MC = \$27,180/year. O&M cost for eight rectangular clarifiers = \$217,440/year.
6. Calculate April 2011 O&M cost of liquid alum feed system [Eq. (93)]. $\mathrm{O\ \&\ MC} = 2{,}122.7x^{0.2919}$. For $x = 94.80$ kg/h ($x = 209$ lb/h), O & MC = \$10,100/year.
7. Update the construction cost of clarifier and alum feed system to February 2013 [Eq. (79)]. February 2013 ENR CCI = 9,453 (Engineering News Record 2013). February 2013 CC = (\$6,261,280 + \$116,670) × (9,453/9,027) = \$6,678,940.
8. Update O&M costs of rectangular clarifier to February 2013. April 2011 O&M cost for rectangular clarifier = \$217,440/ year. Component percentages of electricity, labor, and maintenance materials are 3, 89, and 8%, respectively [Eq. (109)]. Average unit prices of electricity for 2012 are 0.1014/kW · h (Energy Information Administration 2013), and \$50.11 (Engineering News Record 2013). February 2013 O & M cost = [0.03 × (0.1014/0.1006) + 0.89 × (50.11/48.02) + 0.08 × (9453/9027)] × \$217,440/year = \$227,100/year.
9. Update O&M costs of liquid alum feed system to February, 2013 by using similar procedure as in Step 8. February 2013 O&M cost of liquid alum feed system = \$10,930/year.
10. Calculate February 2013 cost of liquid alum feed.
    Annual liquid alum requirement = 422, 521.292 kg/year (931,500 lb/year) $(15.3 \times 20 \times 8.34 \times 365)$. Annual liquid alum cost = 422, 521.292 kg/year × \$0.441/kg = \$958, 098.16/year (931,500 lb/year × \$0.20/lb = \$186,300/year).
11. Calculate the total construction cost.
    Total construction cost = 1.28 × \$6,378,940 = \$8,549,000.
12. Calculate the present worth of annual O&M cost, and equivalent annual cost.
    PW of annual O & M cost = (\$227,100 + \$10,930 + \$186,300)/0.0872 = \$4,866,170. Project PW = \$4,866,170 + \$8,549,000 = \$13,415,170. Equivalent annual cost = \$13,415,170 × 0.0872 = \$1,169,800.

Comparison with Actual Bid Prices

Actual bid prices for one new water treatment plant construction and two water treatment plant expansion projects in Texas were obtained from reputed consulting firms. The bids of these projects included cost breakdown according to treatment units to be constructed for the projects. The costs quoted by the winning bidders of these projects were compared to the prices obtained from the equations. The estimated construction costs were calculated by using the equations provided in Table 2. Single ENR CCIs for the bid years of the projects were used to back-date the costs obtained from the equations. The compared results are provided in Table 4. Nine out of 10 estimates were within ±33% of the bid price. Further validation is recommended by use of the equations and comparison of the costs to the detailed estimates and actual bids.

J. Infrastruct. Syst., 2013, 19(4): 451-464

Table 4. Cost Comparison of Estimated Costs with Actual Bids

Treatment plant	Treatment unit	Capacity	Estimated cost using equations (includes 15% O&P from GC)	Bid price	Percentage difference	Estimate/bid year
$0.1314\ m^3/s$ (3 MGD) expansion	Liquid alum storage and feed	196 mL/ min	\$62,000	\$49,600	20	2006
	Upflow solid contact clarifier	$408.77\ m^2$ (4,400 ft^2)	\$802,700	\$706,500	12	
	Below ground clearwell	$1,336.555\ m^3$ (47,200 ft^3)	\$546,000	\$632,000	−16	
$0.328\ m^3/s$ (7.5 MGD) expansion	Solid contact clarifier	$2 \times 182.46\ m^2$ ($2 \times 1,964\ ft^2$)	\$1,032,700	\$903,280	13	2008
	PAC tower	136.07 kg/day (300 lb/day)	\$537,700	\$475,900	12	
	Clearwell	$5,003.5867\ m^3$ (176,700 ft^3)	\$1,659,500	\$1,021,588	38	
	Chlorine dioxide generation	0.8 mg/L	\$125,800	\$150,000	−20	
$0.525\ m^3/s$ (12 MGD) new construction with pretreatment and infrastructure capacity for ultimate $1.533\ m^3/s$ (35 MGD) capacity	Ozone system including injector	163.29 kg/day (360 lb/day)	\$1,869,000	\$1,599,500	17	2009
	Vertical shaft rapid mixers and flocculators including vertical turbine can pump and sludge collector	Rapid mixer: $2 \times 20.812\ m^3$ ($2 \times 735\ ft^3$) Flocculators: $3 \times 722.64\ m^3$ ($3 \times 25,520\ ft^3$)	\$1,559,500	\$1,267,000	23	
	Clearwell	9,463,529.5 L (2,500,000 gal.)	\$1,398,500	\$1,050,000	33	

Note: GC = general contractor; MGD = million gallons per day; O&P = overhead and profit; PAC = powdered activated carbon.

Conclusions

Generalized construction and O&M cost models are convenient way to develop preliminary cost estimates of water treatment plants during the planning phase. The construction and O&M models presented in this paper are quicker to use than cost curves. The probability of human error is considerably decreased when cost equations are used instead of cost curves. If a short time interval is involved, the procedure for updating construction and O&M costs by using a single ENR cost index is recommended. Designers may use same approach presented in this paper, but with other cost indexes if desired. However, if a long time interval (over eight years) is involved, it is recommended that each of the eight components of construction costs be updated separately by using ENR and BLS indexes.

The cost estimates developed from these equations are from historic data and are intended only for preliminary estimates. They do not represent the accurate cost estimates of the project. The time involved for updated cost to be obtained by the equations is large. Therefore, the accuracy of the estimated costs also depends upon the accuracy of the indexes used to capture price changes in components involved in treatment units. Actual construction costs of the projects heavily depend on the site conditions, weather, competition among bidders and suppliers, and general local and nationwide economic conditions. Therefore, detailed estimates of construction and O&M costs cannot be generalized and must be developed for each specific project based on quantities of materials, equipment, and labor.

References

Bureau of Labor Statistics. (1978). "Producer prices and price indexes: Data for 1978." *Rep. No. 1978*, U.S. Dept. of Labor, Washington, DC.

Bureau of Labor Statistics. (1992a). *Producer price and price indexes: Data of April 1992*, U.S. Dept. of Labor, Washington, DC.

Bureau of Labor Statistics. (1992b). *Producer price index historicals*, U.S. Dept. of Labor, Washington, DC.

Bureau of Labor Statistics. (2011). "Producer price index commodity data." ⟨http://data.bls.gov/PDQ/outside.jsp?survey=wp⟩ (Oct. 27, 2011).

Energy Information Administration. (2011a). "Electricity—Data—U.S. Energy Information Administration." ⟨http://www.eia.gov/electricity/data.cfm#summary⟩ (Oct. 27, 2011).

Energy Information Administration. (2011b). "Natural gas—U.S. Energy Information Administration." ⟨http://www.eia.gov/naturalgas/⟩ (Oct. 27, 2011).

Energy Information Administration. (2011c). "Weekly retail on-highway diesel prices." ⟨http://tonto.eia.doe.gov/oog/info/wohdp/diesel.asp⟩ (Oct. 27, 2011).

Energy Information Administration. (2013). "Average retail price of electricity to ultimate customers." ⟨http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_3⟩ (Feb. 21, 2011).

Engineering News Record. (1978). "Construction scoreboard." *ENR*, 201(16), 93.

Engineering News Record. (2011). "Construction economics." *ENR*, 266(11), 57–58.

Engineering News Record. (2013). "Construction economics." *ENR*, 270(4), 59–60.

Gumerman, R. C., Culp, R. L., and Hansen, S. P. (1979). "Estimating water treatment costs." *Rep. No. EPA-600/2-79-162a-d*, Municipal Environmental Research Laboratory, Office of Research and Development, U.S. EPA, Cincinnati, OH.

Kawamura, S. (2000). *Integrated design and operation of water treatment facilities*, Wiley, New York.

Qasim, S. R., Lim, S. W., Motley, E. M., and Heung, K. G. (1992). "Estimating costs for treatment plant construction." *J. Am. Water Works Assoc.*, 84(8), 56–62.

Qasim, S. R., Motley, E. M., and Zhu, G. (2000). *Water works engineering: Planning, design and operation*, Prentice-Hall, Upper Saddle River, NJ.

Remer, D. S., Lin, S., Yu, N., and Hsin, K. (2008). "An update on cost and scale-up factors, international inflation indexes and location factors." *Int. J. Prod. Econ.*, 114(1), 333–346.

Sharma, J. R. (2010). "Use of cost equations and cost indexes for preliminary cost estimates of water treatment plants." M.S. thesis, Dept. of Civil Engineering, Univ. of Texas at Arlington, Arlington, TX.

J. Infrastruct. Syst., 2013, 19(4): 451-464