Supporting Information for Costs of Advanced Treatment in Water Reclamation

Megan H. Plumlee^a, Benjamin D. Stanford^b, Jean-François Debroux^{a,*}, D. Cory Hopkins^b, Shane A. Snyder^c

^a Kennedy/Jenks Consultants, San Francisco, California, 94107

^b Hazen and Sawyer, Raleigh, North Carolina, 27607

^c Department of Chemical and Environmental Engineering, University of Arizona, Tucson, Arizona, 85721

Table of Contents

1.0	Capital and O&M Cost Tables.....	3
2.0	Capital and O&M Cost Curves.....	16
3.0	Variable Ozone Dose Modification.....	23

List of Tables

Table S-1. Capital Costs for Ozone Contactors.....	3
Table S-2. Capital Costs Associated with Ozone Generation System Components.....	4
Table S-3. Other Capital Costs and Related Services for Ozone System Installations	5
Table S-4. Annual O&M Costs for Ozone	5
Table S-5. Annual O&M Costs for Ozone/H ₂ O ₂	6
Table S-6. Capital Costs for UV/H ₂ O ₂	7
Table S-7. Annual O&M Costs for UV/H ₂ O ₂	8
Table S-8. Capital Costs for Low-Pressure Membranes (MF/UF).....	9
Table S-9. Annual O&M Costs for Low-Pressure Membranes (MF/UF).....	10
Table S-10. Capital Costs for High-Pressure Membrane Filtration (NF/RO).....	10
Table S-11. Annual O&M Costs for High-Pressure Membranes (NF/RO).....	11
Table S-12. Capital Costs for BAC Filters with 10 min EBCT.....	12
Table S-13. Capital Costs for BAC Filters with 20 min EBCT.....	13
Table S-14. Annual O&M Costs for BAC with 10 min EBCT	14
Table S-15. Annual O&M Costs for BAC with 20 min EBCT	14

List of Figures

Figure S-1. Capital costs for ozone systems.	16
Figure S-2. Annual O&M costs for ozone.	17

Figure S-3. Annual O&M costs for ozone/H ₂ O ₂	17
Figure S-4. Capital costs for UV/H ₂ O ₂	18
Figure S-5. Annual O&M costs for UV/H ₂ O ₂	18
Figure S-6. Capital costs for low-pressure membranes (MF/UF).	19
Figure S-7. Annual O&M costs for low-pressure membranes (MF/UF).	19
Figure S-8. Capital costs for high-pressure membrane filtration.	20
Figure S-9. Annual O&M costs for high-pressure membranes (NF/RO).	20
Figure S-10. Capital costs for BAC filters (1–10 MGD).	21
Figure S-11. Capital costs for BAC filters (≥10 MGD).	21
Figure S-12. O&M costs for BAC filters (1–10 MGD).	22
Figure S-13. O&M costs for BAC filters (≥10 MGD).	22

1.0 Capital and O&M Cost Tables

Table S-1. Capital Costs for Ozone Contactors

System Capacity (MGD)^a	Total Volume (gal)^b	No. of Contactors	Contactors Volume (gal)	No. of Cells	Contactors Width (ft)^c	Contactors Cost (\$)
10	34,700	2	17,300	2	15.2	98,400
16	55,500	2	27,700	2	24.4	133,000
21	74,000	2	37,000	3	21.7	161,000
41	141,000	2	70,700	6	20.7	244,000
52	180,000	2	90,100	8	19.8	285,000
200	693,000	6	116,000	10	20.3	1,000,000
288	999,000	8	125,000	10	22.0	1,400,000
389	1,350,000	12	113,000	10	19.8	1,970,000
535	1,860,000	16	116,000	10	20.4	2,680,000

^aBased on an ozone dose of 3 mg/L.

^bBased on a contactor HRT of 5 min.

^cBased on a depth of 24 ft (including 5 ft freeboard), length of 4 ft/cell, not to exceed 10 cells.

Copyright 2014 WateReuse Research Foundation.

Table S-2. Capital Costs Associated with Ozone Generation System Components

System Capacity	Ozone System Size	Ozone Generators	Ozone Contactor Capital Cost	Ozone Equipment Capital Cost	Installation Cost @ 30%	Ozone System Cost	System Capital Unit Cost
(MGD)	(lb/day)^a	(Units × Capacity)	(\$M)^b	(\$M)	(\$M)	(\$M)	(\$M/MGD)
10	250	2 × 125	0.098	1.90	0.57	2.57	0.257
16	400	2 × 200	0.133	2.07	0.62	2.82	0.177
21	534	2 × 267	0.161	3.51	1.05	4.72	0.221
41	1,020	1 × 1020	0.244	2.50	0.75	3.49	0.086
52	1,300	2 × 650	0.285	4.20	1.26	5.74	0.111
200	5,000	2 × 2500	1.002	5.25	1.58	7.8	0.039
288	7,200	3 × 2400	1.404	6.67	2.00	10.1	0.035
389	9,750	3 × 3250	1.972	10.0	3.00	15.0	0.038
535	13,400	4 × 3350	2.682	12.5	3.75	18.9	0.035

^aBased on an ozone dose of 3 mg/L. ^bOzone System costs include ozone generators, LOX system, supplemental nitrogen system, ozone injection or diffusers, ozone destruct units, monitors, and overall system control. ^cOzone equipment capital costs include one additional generator for redundancy, though the redundancy is not reflected in “Ozone System Size”.

Copyright 2014 WateReuse Research Foundation.

Table S-3. Other Capital Costs and Related Services for Ozone System Installations

Cap- acity	Ozone System Cost (Tbl. S-2)	Yard Piping Costs (10%)	Sitework Landscap- ing Costs (5%)	Site Electrical and Control Construction Costs (20%)	All Trades Subtotal	Contractor OH&P @ 15%	Cont- ingency @ 30%	Total Constr- uction Cost	Engineering, Legal, and Admin. Costs	Total Project Cost	Total Unit Cost ^a
(MGD)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M/MGD)
10	2.57	0.257	0.128	0.514	3.47	0.520	1.04	5.03	1.76	6.79	0.68
16	2.82	0.282	0.141	0.565	3.81	0.572	1.14	5.53	1.93	7.46	0.47
21	4.72	0.472	0.236	0.945	6.38	0.957	1.91	9.25	3.24	12.5	0.59
41	3.49	0.349	0.175	0.699	4.72	0.707	1.41	6.84	2.39	9.23	0.23
52	5.74	0.574	0.287	1.15	7.76	1.16	2.33	11.3	3.94	15.2	0.29
200	7.80	0.783	0.391	1.57	10.6	1.59	3.17	15.3	5.36	20.7	0.10
288	10.1	1.01	0.504	2.01	13.6	2.04	4.08	19.7	6.90	26.6	0.09
389	15.0	1.50	0.749	2.99	20.2	3.03	6.06	29.3	10.3	39.6	0.10
535	18.9	1.89	0.947	3.79	25.6	3.83	7.67	37.1	13.0	50.0	0.09

Copyright 2014 WateReuse Research Foundation.

Table S-4. Annual O&M Costs for Ozone

System Capacity (MGD)	Ozone System Size (lb/day) ^a	Energy Consumption (kWh/lb O ₃)	Annual Energy Cost (\$M) ^b	Unit O&M Cost (\$M/MGD)
10	250	6.75	0.0610	0.0061
16	400	6.65	0.0960	0.0060
21	534	6.65	0.128	0.0060
41	1,020	5.75	0.211	0.0052
52	1,300	6.35	0.298	0.0057
200	5,000	5.65	1.02	0.0051
288	7,200	5.65	1.47	0.0051
389	9,750	5.65	1.99	0.0051
535	13,400	5.55	2.68	0.0050

^aBased on an ozone dose of 3 mg/L.^bBased on current electrical pricing of \$0.0988/kWh.

Copyright 2014 WateReuse Research Foundation.

Table S-5. Annual O&M Costs for Ozone/H₂O₂

System Capacity	Ozone System Size	Energy Consumption	Annual Energy Cost	Annual H ₂ O ₂ Cost	Annual Hypochlorite Quenching Cost	Total O&M Cost	Unit O&M Cost
(MGD)	(lb/day) ^a	(kWh/lb O ₃)	(\$M) ^b	(\$M) ^c	(\$M)	(\$M/MGD)	(\$M/MGD)
10	250	6.75	0.0610	0.0340	0.0570	0.152	0.0152
16	400	6.65	0.0960	0.0544	0.0912	0.242	0.0151
21	534	6.65	0.128	0.0714	0.120	0.319	0.0152
41	1,020	5.75	0.211	0.139	0.234	0.584	0.0142
52	1,300	6.35	0.298	0.177	0.296	0.771	0.0148
200	5,000	5.65	1.02	0.680	1.14	2.84	0.0142
288	7,200	5.65	1.47	0.979	1.64	4.09	0.0142
389	9,750	5.65	1.99	1.32	2.22	5.53	0.0142
535	13,400	5.55	2.68	1.82	3.05	7.55	0.0141

^aBased on an ozone dose of 3 mg/L.^bBased on current electrical pricing of \$0.0988/kWh.^cBased on an H₂O₂ dose of 2 mg/L (H₂O₂:O₃=1.0).

Copyright 2014 WateReuse Research Foundation.

Table S-6. Capital Costs for UV/H₂O₂

System Capacity	UV/H₂O₂ System Cost^a	Yard Piping Cost (10%)	Sitework Land-scaping Cost (5%)	Site Electrical and Controls Cost (20%)	Subtotal Construction Cost	Contractor OH&P (15%)	Contingency (30%)	Total Construction Cost	Engineering, Legal, and Admin. Costs (35%)	Total Project Cost^a	Total Unit Cost
(MGD)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M/MGD)
1	0.22	0.02	0.01	0.04	0.30	0.04	0.09	0.23	0.08	0.31	0.31
5	0.61	0.06	0.03	0.12	0.82	0.12	0.25	0.63	0.22	0.85	0.17
10	1.51	0.15	0.08	0.30	2.04	0.31	0.61	1.57	0.55	2.12	0.21
20	2.99	0.30	0.15	0.60	4.04	0.61	1.21	3.11	1.09	4.20	0.21
30	4.45	0.45	0.22	0.89	6.01	0.90	1.80	4.63	1.62	6.2	0.21
40	5.91	0.59	0.30	1.18	7.98	1.20	2.40	6.1	2.15	8.3	0.21
50	7.37	0.74	0.37	1.47	9.95	1.49	2.99	7.7	2.68	10.3	0.21
60	8.84	0.88	0.44	1.77	11.9	1.79	3.58	9.2	3.21	12.4	0.21
70	10.3	1.03	0.51	2.06	13.9	2.08	4.17	10.7	3.74	14.4	0.21
80	11.8	1.18	0.59	2.36	15.9	2.39	4.78	12.3	4.29	16.5	0.21

^a Includes installation cost (30%)

Copyright 2014 WateReuse Research Foundation.

Table S-7. Annual O&M Costs for UV/H₂O₂

System Capacity	Vendor A, Annual Operating H₂O₂ Cost	Vendor A, Annual Operating Hypochlorite Quenching Cost	Vendor A, Annual Operating Energy Cost	Vendor A, Annual Operating Lamp Replacement Cost	Vendor A, Total O&M Cost	Vendor A, Unit O&M Cost	Mean of Vendors A, B, and C, Unit O&M Cost
(MGD)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M/MGD)	(\$M/MGD)^a
1	0.005	0.009	0.02	0.004	0.04	0.042	0.042
5	0.03	0.04	0.09	0.01	0.17	0.035	0.031
10	0.05	0.09	0.19	0.02	0.35	0.035	0.031
20	0.10	0.17	0.37	0.05	0.69	0.035	0.031
30	0.16	0.26	0.56	0.07	1.04	0.035	0.031
40	0.21	0.34	0.74	0.09	1.38	0.035	0.031
50	0.26	0.43	0.93	0.11	1.73	0.035	0.031
60	0.31	0.51	1.11	0.14	2.07	0.035	0.031
70	0.36	0.60	1.30	0.16	2.42	0.035	0.031
80	0.41	0.68	1.48	0.18	2.76	0.035	0.031

^aItemized data for Vendors B & C are not shown but are included in the mean cost presented here.

Copyright 2014 WateReuse Research Foundation.

Table S-8. Capital Costs for Low-Pressure Membranes (MF/UF)

System Capacity	MF/UF System Cost^a	Yard Piping Cost (10%)	Sitework Land-scaping Cost (5%)	Site Electrical and Controls Cost (20%)	Subtotal Construction Cost	Contractor OH&P (15%)	Contingency (30%)	Total Construction Cost	Engineering, Legal, and Admin. Costs (35%)	Total Project Cost	Total Unit Cost
(MGD)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M/MGD)
1	1.5	0.15	0.08	0.31	2.1	0.31	0.62	3.0	1.0	4.0	4.04
2	2.3	0.23	0.11	0.46	3.1	0.46	0.93	4.5	1.6	6.1	3.03
4	3.8	0.38	0.19	0.76	5.2	0.77	1.5	7.5	2.6	10.1	2.53
6	5.3	0.53	0.26	1.1	7.1	1.1	2.1	10.3	3.6	13.9	2.32
8	6.7	0.67	0.34	1.3	9.1	1.4	2.7	13.2	4.6	17.8	2.22
10	7.6	0.76	0.38	1.5	10.3	1.5	3.1	15.0	5.2	20.2	2.02
12	8.7	0.87	0.44	1.7	11.8	1.8	3.5	17.1	6.0	23.0	1.92
14	10.2	1.0	0.51	2.0	13.7	2.1	4.1	19.9	7.0	26.9	1.92
16	11.6	1.2	0.58	2.3	15.7	2.4	4.7	22.7	8.0	30.7	1.92
18	12.4	1.2	0.62	2.5	16.7	2.5	5.0	24.2	8.5	32.7	1.82
20	13.8	1.4	0.69	2.8	18.6	2.8	5.6	26.9	9.4	36.4	1.82
40	26.0	2.6	1.3	5.2	35.1	5.3	10.5	50.9	17.8	68.7	1.72
70	37.5	3.7	1.9	7.5	50.6	7.6	15.2	73.3	25.7	99.0	1.41
80	42.8	4.3	2.1	8.6	57.8	8.7	17.3	83.8	29.3	113	1.41

^aIncludes installation cost (30%)

Copyright 2014 WateReuse Research Foundation.

Table S-9. Annual O&M Costs for Low-Pressure Membranes (MF/UF)

System Capacity	Labor Cost for Membrane Processes	Chemical Cost for Membrane Processes	Membrane Replacement Cost	Energy Cost	Total O&M Cost	Unit O&M Cost
(MGD)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M/MGD)
1.1	0.2	0.1	0.0	0.01	0.40	0.38
2.6	0.2	0.2	0.1	0.04	0.56	0.21
5.3	0.2	0.5	0.2	0.08	0.93	0.18
11	0.3	1.0	0.4	0.16	1.82	0.17
26	0.4	2.3	0.9	0.38	4.01	0.15
53	0.4	4.5	1.8	0.81	7.50	0.14

Copyright 2014 WateReuse Research Foundation.

Table S-10. Capital Costs for High-Pressure Membrane Filtration (NF/RO)

System Capacity	NF/RO System Cost^a	Yard Piping Cost (10%)	Sitework Landscaping Cost (5%)	Site Electrical and Controls Cost (20%)	Subtotal Construction Cost	Contractor OH&P (15%)	Contingency (30%)	Total Construction Cost	Engineering, Legal, and Admin. Costs (35%)	Total Project Cost	Total Unit Cost
(MGD)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M/MGD)
1	3.1	0.31	0.15	0.61	4.1	0.62	1.2	6.0	2.1	8.1	8.08
2	4.6	0.46	0.23	0.92	6.2	0.93	1.9	9.0	3.1	12.1	6.06
4	7.6	0.76	0.38	1.5	10.3	1.5	3.1	15.0	5.2	20.2	5.05
6	10.5	1.1	0.53	2.1	14.2	2.1	4.3	20.7	7.2	27.9	4.65
8	13.5	1.3	0.67	2.7	18.2	2.7	5.4	26.3	9.2	35.6	4.44
10	15.3	1.5	0.76	3.1	20.6	3.1	6.2	29.9	10.5	40.4	4.04
12	17.4	1.7	0.87	3.5	23.5	3.5	7.1	34.1	11.9	46.1	3.84
14	20.3	2.0	1.0	4.1	27.5	4.1	8.2	39.8	13.9	53.7	3.84
16	23.2	2.3	1.2	4.6	31.4	4.7	9.4	45.5	15.9	61.4	3.84
18	24.8	2.5	1.2	5.0	33.4	5.0	10.0	48.5	17.0	65.5	3.64
20	27.5	2.8	1.4	5.5	37.2	5.6	11.1	53.9	18.9	72.7	3.64
40	52.0	5.2	2.6	10.4	70.2	10.5	21.1	102	35.6	137	3.43
70	74.9	7.5	3.7	15.0	101	15.2	30.3	147	51.3	198	2.83
80	85.6	8.6	4.3	17.1	116	17.3	34.7	168	58.7	226	2.83

^aIncludes installation cost (30%)

Copyright 2014 WateReuse Research Foundation.

Table S-11. Annual O&M Costs for High-Pressure Membranes (NF/RO)

System Capacity	Labor Cost for Membrane Processes	Chemical Cost for Membrane Processes	Membrane Replacement Cost	Energy Cost	Total O&M Cost	Unit O&M Cost
(MGD)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M)	(\$M/MGD)
1.1	0.25	0.10	0.04	0.15	0.53	0.51
2.6	0.20	0.22	0.10	0.39	0.91	0.34
5.3	0.22	0.45	0.18	0.81	1.66	0.31
11	0.29	1.00	0.37	1.63	3.28	0.31
26	0.37	2.34	0.92	3.79	7.42	0.28
53	0.42	4.54	1.76	8.07	14.8	0.28

Copyright 2014 WaterReuse Research Foundation.

Table S-12. Capital Costs for BAC Filters with 10 min EBCT

Flow (MGD)^a	1	2	4	6	8	10	20	30	40	60	70	80
Surface area (sf)	174	347	694	1,040	1,390	1,740	3,470	5,210	6,940	10,400	12,200	13,900
Volume GAC (cf)	928	1,860	3,710	5,570	7,430	9,280	18,600	27,800	37,100	55,700	65,000	74,300
Depth GAC (ft)	5.35	5.35	5.35	5.35	5.35	5.35	5.35	5.35	5.35	5.35	5.35	5.35
Structure (\$M)	0.785	0.887	1.09	1.29	1.50	1.70	2.69	3.66	4.62	6.46	7.34	8.21
GAC (\$M)	0.0430	0.0860	0.172	0.258	0.344	0.430	0.860	1.29	1.72	2.58	3.01	3.44
Backwash pumping (\$M)	0.147	0.1990	0.303	0.407	0.511	0.616	1.14	1.66	2.18	3.22	3.74	4.26
Intermediate pumping (\$M)	0.182	0.304	0.506	0.669	0.810	1.01	1.72	2.43	3.04	4.05	4.66	5.06
Process Subtotal (\$M)	1.16	1.48	2.07	2.63	3.16	3.76	6.41	9.04	11.6	16.3	18.8	21.0
Yard piping cost (10%) (\$M)	0.12	0.15	0.21	0.26	0.32	0.38	0.64	0.90	1.16	1.63	1.88	2.10
Sitework costs (5%) (\$M)	0.06	0.07	0.10	0.13	0.16	0.19	0.32	0.45	0.58	0.82	0.94	1.05
Electrical and controls (20%) (\$M)	0.23	0.30	0.41	0.53	0.63	0.75	1.28	1.81	2.31	3.26	3.75	4.20
Trades Subtotal (\$M)	1.56	1.99	2.80	3.55	4.27	5.07	8.65	12.21	15.6	22.0	25.3	28.3
Contractor OH&P (15%)	0.23	0.30	0.42	0.53	0.64	0.76	1.30	1.83	2.34	3.30	3.80	4.25
Contingency (30%)	0.47	0.60	0.84	1.06	1.28	1.52	2.60	3.66	4.68	6.60	7.60	8.50
Total Construction Costs	2.26	2.89	4.06	5.14	6.19	7.35	12.55	17.70	22.6	31.9	36.7	41.1
Engineering, Legal, Admin. (35%)	0.79	1.01	1.42	1.80	2.17	2.57	4.39	6.19	7.91	11.17	12.85	14.37
Total project (\$M)	3.06	3.90	5.48	6.94	8.36	9.92	16.94	23.89	30.5	43.1	49.6	55.4
Unit cost (\$M/MGD)	3.06	1.95	1.37	1.16	1.04	0.99	0.85	0.80	0.76	0.72	0.71	0.69

^a Design based on filter loading rate of 4 gpm/sf.

Additional assumptions:

- Filter structure and backwash pumping costs were determined from McGivney and Kawamura (2008), based on costs in Los Angeles, CA
- 2010 filter media pricing was provided for the GAC product Filtrasorb 300M from Calgon Carbon Corporation
- Intermediate lift pumping costs were determined from Jones and Sanks (2008)
- Energy was based on the 2010 national average unit electrical cost (USEIA 2010), adjusted to 2011 dollars
- Labor was based on the 2010 mean unit labor cost for water/wastewater treatment operators (BLS 2011) and was augmented with a multiplier to account for other overhead costs associated with employment, and adjusted to 2011 dollars.

Copyright 2014 WateReuse Research Foundation.

Table S-13. Capital Costs for BAC Filters with 20 min EBCT

Flow (MGD)^a	1	2	4	6	8	10	20	30	40	60	70	80
Surface area (sf)	174	347	694	1,040	1,390	1,740	3,470	5,210	6,940	10,400	12,153	13,900
Volume GAC (cf)	1,860	3,710	7,430	11,100	14,900	18,600	37,100	55,700	74,300	111,000	130,000	149,000
Depth GAC (ft)	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7
Structure (\$M)	0.785	0.887	1.09	1.29	1.50	1.70	2.69	3.66	4.62	6.46	7.34	8.21
GAC (\$M)	0.0860	0.172	0.344	0.516	0.688	0.860	1.72	2.58	3.44	5.16	6.02	6.88
Backwash pumping (\$M)	0.147	0.199	0.303	0.407	0.511	0.616	1.14	1.66	2.18	3.22	3.74	4.26
Intermediate pumping (\$M)	0.182	0.304	0.506	0.669	0.810	1.01	1.72	2.43	3.04	4.05	4.66	5.06
Process Subtotal (\$M)	1.20	1.56	2.24	2.89	3.51	4.19	7.27	10.3	13.3	18.9	21.8	24.4
Yard piping cost (10%) (\$M)	0.12	0.16	0.22	0.29	0.35	0.42	0.73	1.03	1.33	1.89	2.18	2.44
Sitework costs (5%) (\$M)	0.06	0.08	0.11	0.14	0.18	0.21	0.36	0.52	0.66	0.94	1.09	1.22
Electrical and controls (20%) (\$M)	0.24	0.31	0.45	0.58	0.70	0.84	1.45	2.07	2.65	3.78	4.35	4.88
Trades Subtotal (\$M)	1.62	2.11	3.03	3.90	4.73	5.65	9.81	13.9	17.9	25.5	29.4	33.0
Contractor OH&P (15%)	0.24	0.32	0.45	0.58	0.71	0.85	1.47	2.09	2.69	3.82	4.41	4.95
Contingency (30%)	0.49	0.63	0.91	1.17	1.42	1.70	2.94	4.18	5.38	7.65	8.82	9.89
Total Construction Costs	2.35	3.06	4.39	5.65	6.86	8.19	14.2	20.2	26.0	37.0	42.6	47.8
Engineering, legal, admin. (35%) (\$M)	0.82	1.07	1.54	1.98	2.40	2.87	4.98	7.08	9.09	12.9	14.9	16.7
Total project (\$M)	3.17	4.13	5.93	7.63	9.26	11.1	19.2	27.3	35.1	49.9	57.5	64.5
Unit cost (\$M/MGD)	3.17	2.06	1.48	1.27	1.16	1.11	0.96	0.91	0.88	0.83	0.82	0.81

^aDesign based on filter loading rate of 4 gpm/sf.

Additional assumptions: see Table S-12.

Copyright 2014 WateReuse Research Foundation.

Table S-14. Annual O&M Costs for BAC with 10 min EBCT

Design capacity (MGD)	1	2	4	6	8	10	20	30	40	50	60	70	80
Average flow (MGD) ^a	0.5	1	2	3	4	5	10	15	20	25	30	35	40
Labor (hours/day)	1	1	1	1	1	2	2	2	2	2	2	2	2
GAC replacement (\$) ^b	\$5,550	\$11,100	\$22,200	\$33,300	\$44,400	\$55,400	\$111,000	\$166,000	\$222,000	\$277,000	\$333,000	\$388,000	\$444,000
Energy (\$)	\$18,600	\$37,200	\$74,400	\$112,000	\$149,000	\$186,000	\$372,000	\$558,000	\$744,000	\$929,000	\$1,120,000	\$1,300,000	\$1,490,000
Labor (\$)	\$14,100	\$14,100	\$14,100	\$14,100	\$14,100	\$28,200	\$28,200	\$28,200	\$28,200	\$28,200	\$28,200	\$28,200	\$28,200
Total O&M (\$)	\$38,200	\$62,400	\$111,000	\$159,000	\$207,000	\$270,000	\$511,000	\$752,000	\$994,000	\$1,230,000	\$1,480,000	\$1,720,000	\$1,960,000
Unit O&M (\$/MGD)	0.0765	0.0624	0.0553	0.0530	0.0518	0.0539	0.0511	0.0502	0.0497	0.0494	0.0492	0.0491	0.0490

^aO&M costs were calculated assuming 50% of the design flow capacity but plotted based on 100% of the design flow capacity.

^bFrequency of GAC replacement is 8 years and electrical energy consumption is 1 kWh/1,000 gal.

See Table S-15 for additional assumptions and parameters.

Copyright 2014 WateReuse Research Foundation.

Table S-15. Annual O&M Costs for BAC with 20 min EBCT

Design capacity (MGD)	1	2	4	6	8	10	20	30	40	50	60	70	80
Average flow (MGD) ^a	0.5	1	2	3	4	5	10	15	20	25	30	35	40
Labor (hours/day)	1	1	1	1	1	2	2	2	2	2	2	2	2
GAC replacement (\$) ^b	\$11,100	\$22,200	\$44,400	\$66,500	\$88,700	\$111,000	\$222,000	\$333,000	\$444,000	\$554,000	\$665,000	\$776,000	\$887,000
Energy (\$)	\$18,600	\$37,200	\$74,400	\$112,000	\$149,000	\$186,000	\$372,000	\$558,000	\$744,000	\$929,000	\$1,120,000	\$1,300,000	\$1,490,000
Labor (\$)	\$14,100	\$14,100	\$14,100	\$14,100	\$14,100	\$28,200	\$28,200	\$28,200	\$28,200	\$28,200	\$28,200	\$28,200	\$28,200
Total O&M (\$)	\$43,800	\$73,500	\$133,000	\$192,000	\$252,000	\$325,000	\$622,000	\$919,000	\$1,220,000	\$1,510,000	\$1,810,000	\$2,110,000	\$2,400,000
Unit O&M (\$/MGD)	0.0876	0.0735	0.0664	0.0641	0.0629	0.0650	0.0622	0.0612	0.0608	0.0605	0.0603	0.0602	0.0601

^aO&M costs were calculated assuming 50% of the design flow capacity but plotted based on 100% of the design flow capacity.

^bFrequency of GAC replacement is 8 years and electrical energy consumption is 1 kWh/1,000 gal.

Additional assumptions and parameters:

- The physical structure was based on a concrete gravity filter design
- The bulk density of GAC was assumed to be 0.45 g/cm³
- The unit cost of GAC was assumed to be \$1.65/lb
- GAC installation costs were assumed to be approximately 30% of the GAC media costs
- The filter structure costs were based on Figure 5.5.25b in McGivney and Kawamura (2008)
- The backwash pumping costs were based on Figure 5.5.29 in McGivney and Kawamura (2008)
- The intermediate pumping costs were based on Figure 29-7 in Sanks et al. (1998)

- The GAC replacement frequency was assumed to be 8 years
- Unit electrical costs were assumed to be \$0.0988/kWh (U.S. Energy Information Administration, 2010)
- The average flow was approximated as half of the rated filter capacity
- The mean labor rate was assumed to be \$20.27 for water/wastewater treatment plant operators (U.S. Bureau of Labor Statistics, 2011) $\times$ 1.85 for overhead
- The annual average inflation rate was assumed to be 3.10% (U.S. Bureau of Labor Statistics, 2011) and was used to adjust 2010 costs for GAC media, electricity, and labor rates
- The following construction cost indices were used: structure and backwash pumping, CCI 8889; intermediate pumping, CCI 4500; current ENR CCI and GAC cost, CCI 9116 (ENR.com, 2011).

Copyright 2014 WateReuse Research Foundation.

2.0 Capital and O&M Cost Curves

The following figures present capital and O&M cost curves developed for select advanced treatment unit processes. These figures plot the total costs tabulated in the preceding tables in this SI. The capital costs include contractor OH&P (15%) and contingency (30%).

Figure S-1. Capital costs for ozone systems.

Dashed lines represent -30% to +50% error consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

Figure S-2. Annual O&M costs for ozone.

Based on an ozone dose of 3 mg/L.

Dashed lines represent -30% to +50% error consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

Figure S-3. Annual O&M costs for ozone/H₂O₂.

Based on an ozone dose of 3 mg/L and an H₂O₂ dose of 2 mg/L (H₂O₂:O₃=1.0).

Dashed lines represent -30% to +50% error consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

Figure S-4. Capital costs for UV/H₂O₂.

Dashed lines represent -30% to +50% error consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

Figure S-5. Annual O&M costs for UV/H₂O₂.

Dashed lines represent -30% to +50% error consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

Figure S-6. Capital costs for low-pressure membranes (MF/UF).

Dashed lines represent -30% to +50% error consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

Figure S-7. Annual O&M costs for low-pressure membranes (MF/UF).

Dashed lines represent -30% to +50% error, consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

Figure S-8. Capital costs for high-pressure membrane filtration.

Dashed lines represent -30% to +50% error, consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

Figure S-9. Annual O&M costs for high-pressure membranes (NF/RO).

Dashed lines represent -30% to +50% error consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

Figure S-10. Capital costs for BAC filters (1–10 MGD).

Dashed lines represent -30% to +50% error, consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

Figure S-11. Capital costs for BAC filters (≥10 MGD).

Dashed lines represent -30% to +50% error, consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

Figure S-12. O&M costs for BAC filters (1–10 MGD).

Dashed lines represent -30% to +50% error, consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

Figure S-13. O&M costs for BAC filters (≥10 MGD).

Dashed lines represent -30% to +50% error, consistent with a conceptual-level estimate.

Copyright 2014 WateReuse Research Foundation.

3.0 Variable Ozone Dose Modification

The example cost estimates provided in the main report for the ozone-based treatment trains were developed for an ozone dose of 3 mg/L. To allow the cost estimator to account for changes in ozone dose to target a range of water quality objectives, a correction factor was developed and is presented here. The correction factor is based on the following three assumptions/simplifications:

- The ozone system costs (generator, wiring, installation, etc.) need to be proportionally increased or decreased to account for changes in planned ozone dose.
- The ozone contactor size and other required elements of construction will not be changed as the volume of water being treated remains the same.
- The power costs associated with changing the ozone dose can be extrapolated in a linear fashion and used to adjust the annual O&M costs.

On the basis of these assumptions, the capital and annual O&M costs specific to the ozone system were plotted against the design flow (Figure S-14). These plots, which proved to be linear, can be described by the following regression equations:

$$\text{Ozone System Capital Costs (in \$M)} = 0.0294 \times \text{Capacity (in MGD)} + 2.8$$

$$\text{Ozone System Annual O\&M Costs (in \$M)} = 0.005 \times \text{Capacity (in MGD)} + 0.02$$

Figure S-14. Capital and annual O&M costs specific to ozone equipment.

Based on an ozone dose of 3 mg/L.

Copyright 2014 WateReuse Research Foundation.

The steps necessary to make the correction are listed below, which estimate the capital and O&M costs associated with an increased or decreased ozone dose by calculating the change in ozone system-specific costs associated with the same relative change in design flow. If a 10 MGD facility prefers a 6 mg/L ozone dose (i.e., an increase by a factor of 2 over the 3 mg/L baseline), the additional costs can be estimated by calculating the change in capital and O&M costs compared to a 3 mg/L ozone system at a 20 MGD facility (i.e., an increase by a factor of 2 over the 10 MGD design).

This process is summarized in the following steps:

- (1) Determine the ratio (r) of the target ozone dose to the baseline ozone dose (e.g., target dose is 6 mg/L, baseline is always 3 mg/L, $r=2.0$)
- (2) Calculate the total capital costs for the facility's design flow using the regression equations summarized in Table 1 (main text) for a custom treatment train or the data in Table 4 for predetermined treatment trains and flow rates
- (3) Calculate the total annual O&M costs for the facility's design flow using the regression equations summarized in Table 1 for a custom treatment train or the data in Table 5 for predetermined treatment trains and flow rates
- (4) Use the following equation to calculate the increase/decrease in capital cost (ozone system alone) because of the higher/lower design dose:

$$\Delta \text{Capital } (\$M) = 0.0156 \times \text{Design Capacity (in MGD)} \times (r - 1)$$
- (5) Use the following equation to calculate the increase/decrease in annual O&M cost (ozone system alone) because of the higher/lower design dose:

$$\Delta \text{O\&M } (\$M) = 0.005 \times \text{Design Capacity (in MGD)} \times (r - 1)$$
- (6) Adjust the facility capital and annual O&M costs from (2) and (3) for the increased/decreased costs in (4) and (5), respectively, to account for the modified ozone dose

Using these steps, the adjusted capital costs for a 10 MGD O₃-BAC facility operating with a 6 mg/L ozone dose would be \$16M + \$0.29M = \$16.3M, where \$16M is the cost assuming 3 mg/L (see Table 4 of main text) and \$0.29M is the correction factor, and the adjusted annual O&M costs would be \$0.6M + \$0.05M=\$0.7M.