Finding the Optimum UV Disinfection Location in a Large Water Treatment Plant

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ABSTRACT

In its continuous pursuit of innovative technologies that provide the best water and service to its customers, the Greater Cincinnati Water Works (GCWW) is evaluating UV disinfection for meeting customer expectations and future regulations. The GCWW has completed extensive studies to establish the feasibility of fitting a UV system into the existing footprint and hydraulic profile of the Richard Miller Treatment Plant (RMTP).

To select the optimum UV system given the site-specific issues, analyses that were completed included hydraulic evaluations and a cost-effectiveness of alternative UV technologies for the potential locations in the plant flow. This evaluation compared the respective efficiencies of UV equipment currently available based on power usage, space requirements, and capital and O&M costs. The evaluation included both low-pressure high-output and medium-pressure systems. Among available technologies, only three proven UV units are offered in sizes suitable for installation in a facility treating up to 240 mgd (908 ML/d). A cost-benefit analysis was conducted on the three systems. The annualized cost includes equipment, facilities construction and operation/maintenance.

A benefit ranking system was developed. Evaluation criteria were identified and the relative importance established. The analysis indicated that all three UV systems evaluated could be implemented cost-effectively at RMTP. The hydraulic feasibility of adding UV technology to the existing treatment processes was addressed. Plant hydraulic conditions were analyzed using both conventional and CFD models. It was determined that a UV treatment facility could be added to the treatment train downstream of the GAC facility without the need for additional pumping.

A series of cost-benefit analyses were conducted to determine the optimum location for the UV facility in the treatment train. The benefit scoring built on the process developed for analysis of the UV technologies and was expanded to address issues related to location. Initial and life cycle costs were considered in the evaluation, along with non-economic criteria including a vast array of parameters related to water quality, operations, reliability, maintenance, and flexibility. The impact of water quality on UV equipment and operations at the different locations was also factored into the analyses. Based on the cost-benefit analysis, the alternative consisting of adding a new UV facility between the GAC facility and the clearwell was recommended for RMTP.

BACKGROUND

In its continuous pursuit of unfailing public health protection through the application of appropriate and innovative technologies, the Greater Cincinnati Water Works (GCWW) is evaluating ultraviolet (UV) disinfection as a technology for meeting customer expectations and future regulations. The GCWW has completed extensive desktop and laboratory studies of UV disinfection at the 240 mgd (908 ML/d) Richard Miller Treatment Plant (RMTP). These studies focused on scenario assessments of long-term disinfection needs, such as the inactivation of Cryptosporidium, Giardia, and other waterborne pathogens, as well as limiting the formation of disinfection byproducts (DBPs).

PURPOSE

This paper describes the cost-benefit analyses that were performed to determine the optimum location for the UV disinfection equipment in the RMTP. The analysis was performed in a series of steps to compare and evaluate location alternatives. As any alternative was eliminated from consideration the analysis was revised to compare the remaining alternatives. At each step, the cost analysis was based on increasingly detailed information.

LOCATION ALTERNATIVES

Based on site visits and a study of the RMTP, the following four location alternatives for the UV equipment were identified:

Alternative 1 –
Filtered Water prior to pump station

Alternative 2 –
Filtered Water on pump discharge

Alternative 3 –
GAC-Contacted Water on each contactor effluent

Alternative 4 –
GAC-Contacted Water prior to clear well

The four alternatives are described herein and are presented graphically in Figure 1.

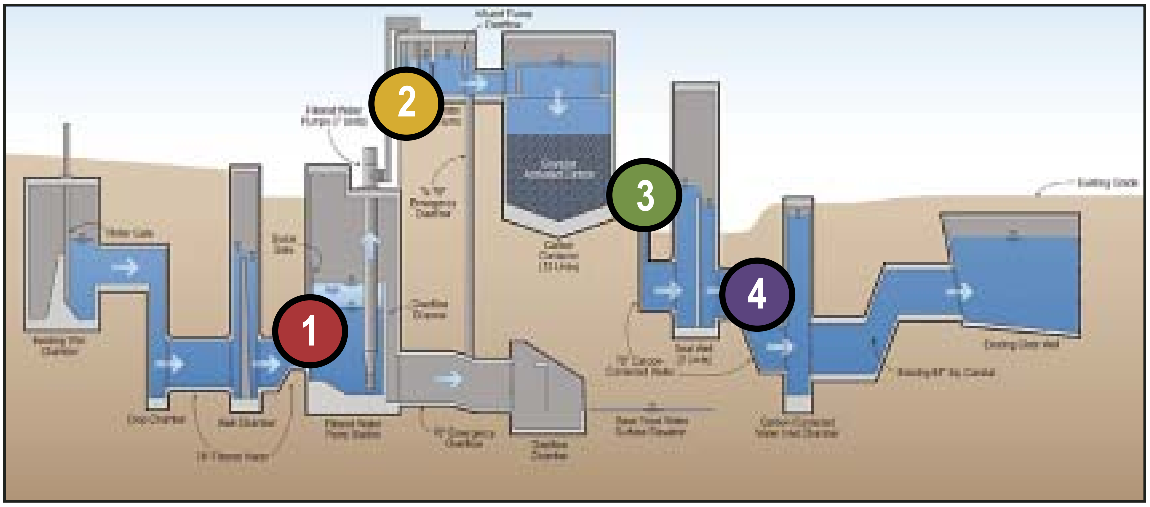


Figure 1. *UV Equipment Location Alternatives*

Alternative 1 – Filtered Water Prior to Intermediate Pump Station

The RMTP hydraulic profile indicates that it is possible to retrofit a UV facility without pumping, that is, gravity flow, between the sand filters and the GAC contactors. The UV facilities would be housed in a separate and new building. Based on a preliminary site evaluation, the new UV building would be located east of the GAC building next to the electrical substation.

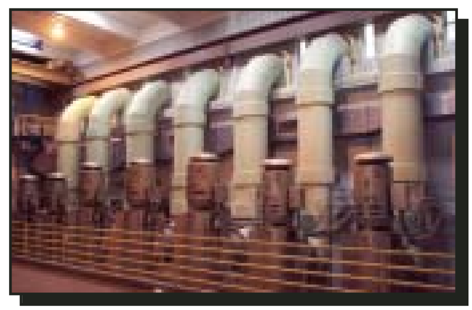
Advantages

A dedicated building would provide better facility layout, less conflict with existing structures and equipment, and easier equipment access for maintenance. The new building also would provide the opportunity to perform on-site validation of a UV full-scale reactor, if desired. Both Low Pressure High Output (LPHO) and Medium Pressure (MP) UV technologies could be implemented at this location. Housing the UV facilities in a separate building would allow the flexibility of configuring piping to routing filtered effluent through the UV facility and bypassing GAC, if desired.

Disadvantages

The design UV transmittance (UVT) for Alternative 1 would be approximately 87% compared to a minimum UVT of 96% post GAC. The lower UV transmittance would result in higher capital and operation and maintenance (O&M) costs. The larger relative size of the UV equipment might also have an impact on the power supply to the RMTP and the size of the uninterruptible power supply (UPS) system. The head loss caused by the UV facility would decrease available head on the sand filters. In addition, the total organic carbon (TOC) of the sand-filtered water is higher than that of the GAC-contacted water and would have higher potential for UV DBPs. No DPBs are known to occur with UV disinfection, but the higher organic content of the filtered effluent poses a slightly greater potential for formation of byproducts.

Alternative 2 – Filtered Water on Pump Discharge



For Alternative 2, the UV facility would be housed in the existing Filtered Water Pump Station on the discharge piping from the pumps. Effluent from the UV reactors would be routed to the GAC influent distribution channel. The UV facility would require platforms for maintenance and access to the UV reactors. Depending on the final UV reactor sizes, additional pumps and modifications of existing pumps and piping might be needed to accommodate the UV reactor, flowmeter, and isolation valves. The existing pumps and discharge piping could be modified to accommodate the additional head loss caused by the UV reactors.

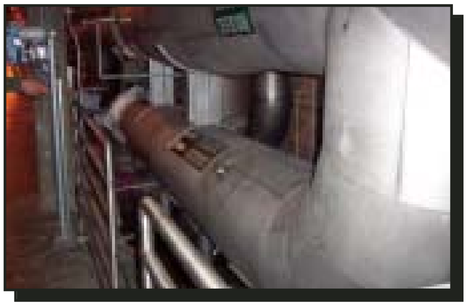
Advantages

Housing the UV facility in the existing Filtered Water Pump Station would reduce overall construction costs. As with Alternative 1, having the UV facility before GAC would provide the opportunity for bypassing GAC if desired.

Disadvantages

The design UV transmittance for Alternative 2 is the same as Alternative 1, resulting in the same need for additional lamps and associated equipment. This increases capital and operating costs. The significant pipe modifications required could result in tight space and accessibility issues. The larger relative size of the UV equipment might also have an impact on the power supply to the RMTP and the size of the UPS system. The TOC of the filtered water is higher than that of the GAC-contacted water and would have higher potential for UV DBPs. In addition, surge and water hammer analyses would be needed to evaluate pump operation on UV reactor and lamp integrity. Because of space constraints, only MP UV lamp technology would be applicable. Piping constraints make on-site UV full-scale reactor validation less feasible.

Alternative 3 – GAC-Contacted Water on Each Contactor Effluent



For Alternative 3, the UV reactors would be installed on the effluent piping of each of the GAC contactors. The GAC effluent piping diameter is 30 inches, which will readily accommodate a MP UV reactor for the 22 mgd (83 ML/d) flowrate per GAC contactor.

Advantages

At any one time, the carbon media in each of the GAC contactors have varying service lives since the last regeneration. This can result in minor differences in the water quality produced by each contactor. By placing each UV reactor on the discharge pipe from a single GAC contactor this alternative permits the reactor setting to be tailored to the specific water quality of the coupled GAC reactor, which may reduce energy demands. The GAC-contacted water has a minimum UV transmittance of 96 percent and, thus, lower capital and O&M UV equipment costs than Alternatives 1 and 2. Because each GAC contactor effluent piping is equipped with isolation valves and flow measurement that could serve both the GAC and the UV units, this option offers the least head demands. This location provides the option for a full-scale UV reactor to be thoroughly tested during the demonstration study, producing full-scale operation and maintenance data. Placing the UV reactor after GAC, as confirmed by the initial studies by the GCWW, would result in no increase in DBPs. The low number of UV lamps would also translate into lower maintenance requirements. Less UV equipment results in lower power requirements and a smaller UPS system, if desired.

Disadvantages

The flexibility to bypass the GAC or UV facility would not be possible with the existing piping arrangement. The head loss through UV reactors would reduce available head for GAC contactors. Because of space constraints, only MP UV lamp technology can be considered. Having the UV reactors in the GAC building pipe gallery could result in tight space and accessibility issues. Alternative 3 would require significant attention to locating power supply panels to mitigate electrical harmonics issues.

Alternative 4 – GAC-Contacted Water Prior to Clear Well

The UV facilities would be housed in a separate and new building. Based on a preliminary site evaluation, the new UV facility building could be located northeast of the GAC building.

Advantages

Similar to Alternative 3, the GAC-contacted water has a minimum UV transmittance of 96 percent. This high-quality water would require less UV equipment and, thus, result in lower capital and O&M costs. A dedicated building would provide better facility layout, less conflict with existing structures and equipment, and easier equipment access for maintenance. The new building would also provide the opportunity to perform on-site validation of a UV full-scale reactor, if desired. Both LPHO and MP UV technologies could be implemented at this location. Similar to Alternative 3, placing the UV reactor after GAC would result in no increases in DBPs. The hydraulic analysis of the RMTP indicates that gravity flow through the UV units in this location could be accomplished without the need for additional pumping and without the loss of clearwell storage. Finally, the flexibility to bypass the UV facility with GAC-contacted water could also be provided.

Disadvantages

The location of the UV building will need to be outside of the existing fence line, requiring considerable civil works to construct and the resulting additional capital costs.

COST-BENEFIT ANALYSES

Initial Screening of Location Alternatives

Decisions, such as selection of the location for a new UV installation, are complex and include consideration of economic, technical, and qualitative issues. Certainly, several factors influence alternative selection. The lowest-cost alternative does not necessarily provide the greatest benefit to GCWW customers. The following cost-benefit analysis is an analytical tool that comparatively assesses the costs and benefits of an alternative in support of a rational decision-making process.

The following economic criteria were used for the initial screening evaluation of the four locations:

- 20-year planning period
- 6% interest rate

For the initial screening of location alternatives, the capital and operating costs included only the major cost items and were developed for comparative (i.e., screening) purposes only. The non-economic factors are attributes of the UV location alternatives that the project team considered important.

The cost-benefit analysis undertaken involved the following steps:

1. Identifying non-monetary criteria.
2. Force ranking the non-monetary criteria.
3. Scoring alternatives in terms of their relative benefits for each of the non-monetary criteria.
4. Multiplying scores by the model weights and totaling for each alternative.
5. Developing capital and operating cost information for each alternative.
6. Comparing the relative cost and benefits for each alternative.

The following sections describe each of these steps.

Evaluation Criteria for Location Alternatives

During meetings with GCWW staff, the project team members were asked to identify all non-economic criteria that should be considered. A project workshop was conducted on October 2, 2003, to finalize primary and secondary criteria. The primary criteria and associate sub-criteria were selected and are presented in Table 1.

Table 1. *Non-economic criteria*

Primary Criteria	Example Evaluation Sub-criteria
Water Quality	DBP potential, regulatory acceptance
Operation	Construction coordination, head loss
Reliability	Testing of equipment against industry standards, performance validation
Maintenance	Potential for gravity flow, accessibility
Flexibility	Ability to accommodate MP and LP, flexibility in reactor sizing

After the primary evaluation criteria were identified and agreed on, they were force ranked in a one-on-one comparison. Following the force ranking, relative weights were assigned according to perceived importance of each criterion. The next step in the process was to conduct the non-economic evaluation of the various location alternatives based on the evaluation criteria. Scores from 1 to 5, with 5 as the highest and 1 as the lowest, were assigned to each alternative for each criteria. Table 2 shows the group consensus reached in the scoring of each alternative against the five primary criteria. These primary criteria scores are the summation of scores developed for each of the sub-criteria.

Table 2. *Ranking of UV Location alternatives*

Criterion	Weightings	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Water Quality	100	2.9	2.9	3.1	3.9
Operation	94	3.4	3.8	4.0	1.7
Reliability	86	3.9	1.7	2.9	5.0
Maintenance	73	2.7	2.0	3.7	3.7
Flexibility	59	5.0	1.5	1.0	5.0

Using the weighting for each criterion and scores, the “benefit” was calculated for each location alternative. The results are shown graphically in Figure 2.

Life Cycle Comparative Costs (Economic Evaluation)

The next step in the alternative screening was to determine the cost impacts of each of the proposed locations. Table 3 shows the life cycle costs based on the historical costs obtained for UV equipment placed in similar locations at other facilities. These costs include the annualized initial equipment (capital) costs and the yearly O&M costs based on average flow and water quality conditions at the RMTP.

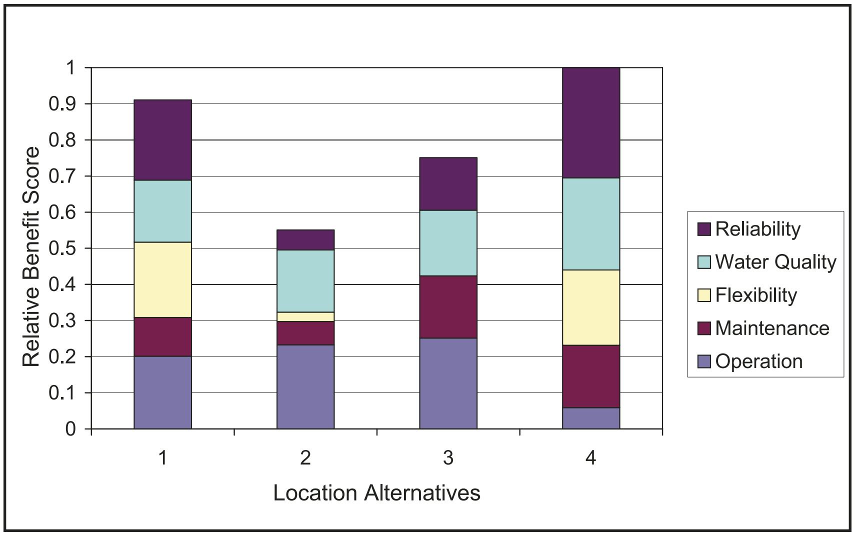


Figure 2. *Normalized Benefit Score for four UV Equipment Location Alternatives*

Table 3. *Comparative Life Cycle Costs*

Criterion	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Comparative Annualized capital cost ($M)[1,2]	0.64	0.78	0.45	0.51
Comparative Annual operating cost ($M)[3]	0.39	0.43	0.24	0.24
Comparative Total Annualized Cost ($M)[4]	1.04	1.22	0.68	0.74
Relative benefit	0.50	0.30	0.41	0.55
Cost/benefit ($M)	**2.07**	**4.06**	**1.67**	**1.35**

1. Based on comparative capital cost of UV equipment, building, valving, flow meters and 20-year amortized cost of power, maintenance, and operation. Actual costs will vary depending on final design details and other factors.
2. Note, the capital costs shown are for alternatives screening purposes only, and do not include all construction costs, which were developed in later analysis (see below).
3. Operating costs of power and O&M. Actual costs will vary depending on final design details and other factors.
4. Total annualized cost based on 20 years and 6 percent.

Figure 3 presents the relative benefits as well as the total annualized costs and the cost-benefit values for each of the four alternative locations. The cost-benefit ratio was calculated by dividing the annualized total costs by the relative benefit score. Figure 3 shows also the cost-benefit ratio, calculated as the total annualized costs over the relative benefits.

Screening Conclusions and Recommendations

Based on the results presented in Figure 3 and the discussion during the project workshop, the initial screening showed that Alternative 2 has the fewest benefits and a high cost that result in the poorest cost-benefit ratio. (Because this ratio is cost divided by benefit, low values are best.) Thus, Alternative 2 was eliminated from further analysis.

Location Alternatives 1, 3, and 4 offer cost-benefit ratios within a close range. Based on these results, it was determined to perform further hydraulic analyses and develop conceptual layouts and cost estimates for Location Alternatives 1, 3, and 4 before selecting the preferred location for the proposed UV facilities.

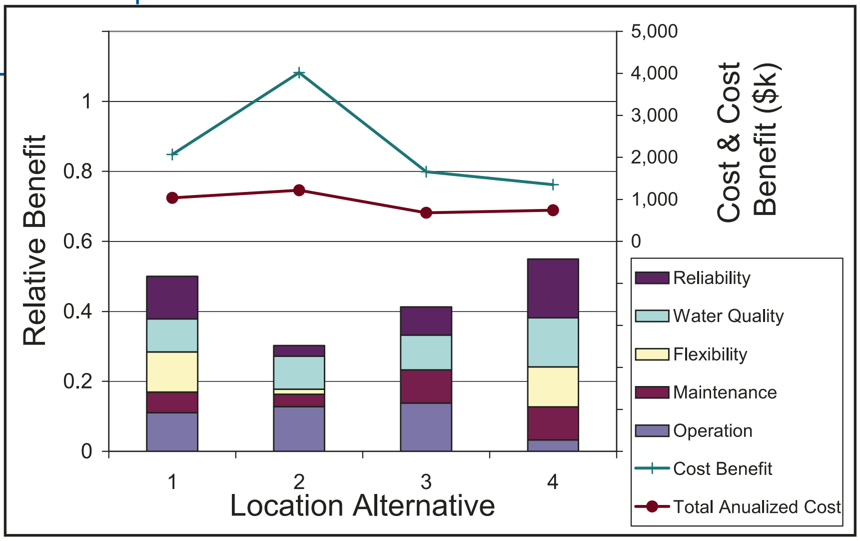


Figure 3. *Benefit, Total Annualized Cost, and Cost-Benefit Ratio for the four locations*

Conceptual Layouts and Cost Estimates

The conceptual layouts and cost estimates were developed for all three leading UV equipment suppliers – namely Trojan, Calgon, and Wedeco. A cost benefit analysis was also performed to compare these UV equipment suppliers. It should be noted that because of site constraints at Location Alternative 3, only UV equipment provided by Trojan was considered.

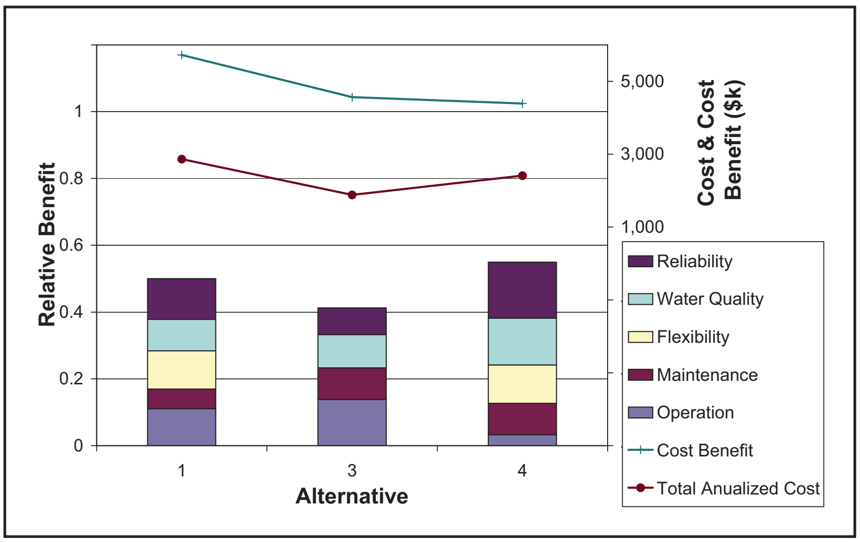
Conceptual layouts were developed for two technologies, one MP (Trojan) and one LPHO (Wedeco), at Locations 1 and 4. The size of the MP reactor offered by Calgon for RMTP falls in the range between the Trojan unit and the Wedeco LPHO unit, hence it was not necessary to develop a separate layout for Calgon. Trojan equipment was used to develop a conceptual layout at Location 3. Based on these layouts and cost estimates provided by the three UV manufacturers, order-of-magnitude cost estimates were developed for the above alternatives.

Cost Benefit Analysis for Locations 1, 3, and 4

Based on the conceptual layouts, and benefit scores developed during the initial screening of location alternatives, and the order of magnitude cost estimates, a more detailed cost-benefit analysis was performed for Locations 1, 3, and 4. By this stage of the project, vendor quotes had been obtained for the UV reactors for use in the cost-benefit analysis. The life cycle analysis had also been refined to consider that structures should be assigned a 50-year life versus 10 years for equipment.

The cost-benefit results presented in Figure 4 indicate that Location Alternatives 3 and 4 offer the GCWW the lowest cost benefit ratios (i.e., best options). Detailed hydraulic evaluations of existing facilities at the RMTP (the results of which are presented elsewhere) show that the proposed UV process can be accommodated at all locations without additional pumping. Based on the cost benefit results and the hydraulic evaluations, Location Alternatives 3 and 4 were selected for further and final comparison. Location Alternative 1 was eliminated from any subsequent analyses.

Figure 4. ***Benefit, Total Annualized Cost, and Cost-Benefit Ratio for Location Alternatives 1, 3, and 4***



Cost Benefit Analysis for Locations 3 and 4

The elimination of Location Alternative 1 requires that the evaluation criteria weights and benefit scores be modified for proper comparison between Location Alternatives 3 and 4. For example, both location alternatives will treat the same water which renders the water quality benefit equal for both locations. The revised cost benefit ratios for analysis of Location Alternatives 3 and 4 are presented in Figure 5. The results indicate that Location Alternative 4 offers the better cost-benefit ratio. Location Alternative 4 is thus recommended for the proposed UV disinfection facilities. Location Alternative 4 benefits that support the decision to implement the UV at this location include:

- Increased flexibility to implement future advancements in UV technology because of improved access and retrofit capabilities.
- Increased flexibility to implement different UV technologies (Location Alternative 3 limits competition of UV bids to one manufacturer).
- Reduced GAC operating complexity because of separation of GAC and UV units; Location Alternative 3 ties the two processes together.
- Increased flexibility to bypass GAC if desired.
- Improved operability and maintainability because of improved access to equipment.
- Optimized operations performance because the new location permits optimizing flow path through the reactors.
- Provision of space for storage of spare parts and for performing maintenance (Location Alternative 3 will need additional space constructed for associated maintenance needs).

SUMMARY AND RECOMMENDED LOCATION FOR UV DISINFECTION FACILITIES

Four alternatives for the UV equipment site location were identified at the RMTP. These represented the most feasible sites for the proposed UV facilities. The four location alternatives were as follow:

Alternative 1 –
Filtered Water prior to pump station

Alternative 2 –

Filtered Water on pump discharge

Alternative 3 –
GAC-Contacted Water on each contactor effluent

Alternative 4 –
GAC-Contacted Water prior to clear well

The four alternatives are presented graphically in Figure 1. Detailed hydraulic evaluations indicated that the RMTP can accommodate the proposed UV disinfection facilities at all of these locations. No additional pumping would be required.

Cost benefit analyses were performed in three steps to reach the most cost-effective solution for the GCWW.

The results of the three cost benefit analyses are presented in Figures 3, 4, and 5. Location Alternatives 1 and 2 were eliminated in the first and second cost benefit analysis, respectively. The final cost benefit analysis between Location Alternatives 3 and 4 (Figure 5) showed that Location 4 offers the GCWW the lowest cost benefit ratio and was recommended for the proposed UV disinfection facilities at the RMTP. A sensitivity analysis of the life cycle planning period was done and showed that the time period selected did not impact the final recommendations.

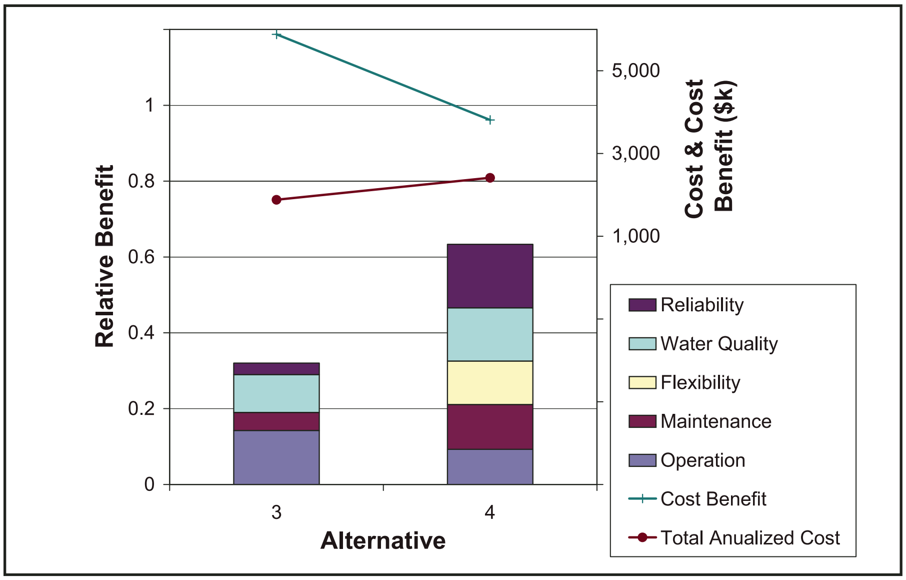


Figure 5. *Benefit, Total Annualized Cost, and Cost-Benefit Ratio for Location Alternatives 3 and 4*