United States
Environmental Protection
Agency

Framework for Comparing Alternatives

For Water Quality Surveillance and Response Systems

Office of Water (MC 140) EPA 817-B-15-003 June 2015

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Acknowledgements

The document was developed by the USEPA Water Security Division, with additional support provided under USEPA contract EP-C-10-060. Peer review of this document was provided by:

- Kevin Gertig, Fort Collins Utilities
- Julie Hunt, Trinity River Authority of Texas

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Abbreviations

C/C	Cost vs. capability ratio
CCS	Customer Complaint Surveillance
CM	Consequence Management
Cont	Local controller used for data transmission
Conv	Sensor suite to measure conventional parameters
DG	Design goal
DOE	Department of Energy
DPD	N,N-diethyl-p-phenylenediamine;
ESM	Enhanced Security Monitoring
IT	Information technology
LCab	Large cabinet
LCCE	Lifecycle cost estimate
NIST	National Institute of Standards and Technology
O&M	Operations and Maintenance
OWQM	Online Water Quality Monitoring
PHS	Public Health Surveillance
PO	Performance objective
RUL	Remaining useful life
S&A	Sampling and Analysis
SCab	Standard cabinet
SPV	Single present value
SRS	Water Quality Surveillance and Response System
TEVA-SPOT	Threat Ensemble Vulnerability Assessment – Sensor Placement Optimization Tool
TUL	Total useful life
UPV	Uniform present value
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
UVis	UV-Visible spectral absorption instrument
WHEAT	Water Health and Economic Analysis Tool

Section 1: Introduction

1.1 Scope of Guidance

This document provides guidance for selecting the most appropriate ***Water Quality Surveillance and Response System*** (SRS) design for a utility from a set of viable alternatives. It provides a framework that guides the user through an objective, stepwise analysis for ranking multiple alternatives and describes, in general terms, the types of information necessary to compare the alternatives.

Before the comparative framework described in this document can be applied, the SRS design alternatives to be compared must be developed. These design alternatives should be informed by ***design goals, performance objectives*** and ***constraints*** established for the SRS (USEPA, 2015). Design goals define the specific ***benefits*** that a utility would like to realize through deployment of an SRS. Benefits obtained through operation of an SRS can be considered in two broad categories: (1) those that support routine operation and management of the distribution system and (2) those related to detection of and response to water quality incidents in the distribution system. Performance objectives define metrics to gauge how well the SRS achieves the established design goals. Constraints, often driven by practical and financial considerations, dictate the requirements or limitations within which the SRS must be designed and operated. The same information used to develop the alternatives (design goals, performance objectives and constraints) may be useful as ***evaluation criteria*** in the analysis of alternatives.

LIMITATIONS OF THIS GUIDANCE

The scope of this document is limited to defining the framework for comparison of viable and well-defined SRS design alternatives. It does not describe how to develop a set of viable SRS design alternatives.

For guidance on developing viable SRS designs, please visit the USEPA Water Security website: http://water.epa.gov/infrastructure/watersecurity/index.cfm

1.2 Application of Guidance

The framework presented in this guidance can be applied at a variety of scales including alternatives for the design of the overall SRS, design of an individual SRS ***component***, and design or selection of a specific ***asset***. An asset is a specific piece of equipment or other item used in the implementation of an SRS. **Table 1-1** describes these three scales, providing example alternatives that could be analyzed at each scale and the level of definition required to complete the analysis. For effective application of the framework, all alternatives must be adequately and consistently defined at the scale being analyzed. Furthermore, the same cost elements should be included for all alternatives being compared.

The number of alternatives selected for comparison is limited by the scale of the system being considered. Comparison of large-scale designs, such as that for an SRS, works better with a relatively small number of alternatives due to the inherent complexity of the entire system. At a smaller scale, such as a component or asset, it becomes feasible to compare a larger number of alternatives.

Table 1-1. Scales of SRS Design Alternatives that can be Considered in a Comparative Analysis

Scale of Comparison	Example Design Alternatives	Example Required Level of Definition for the Scale of Comparison
System	Alternative SRS designs considering components to be included in the system, with a trade-off between cost and capability: 1. Base SRS (CM, CCS, PHS, S&A) 2. Base SRS + OWQM 3. Base SRS + ESM	The components to be included in the SRS. Attributes of conceptual-level design for each component such as equipment, information management systems, additional personnel, and partner involvement necessary for each alternative. Order of magnitude cost estimates for each alternative.
Component	Alternative OWQM designs, with a trade-off between number of monitoring stations and number of parameters monitored: 1. Monitoring for conventional parameters (chlorine residual, pH, and conductivity) at 20 locations in the distribution system 2. Monitoring for conventional parameters plus UV-Visible spectral absorption at 10 locations in the distribution system 3. Monitoring for conventional parameters at 12 locations and for conventional parameters plus UV-Visible spectral absorption at 3 additional locations in the distribution system 4. Monitoring for conventional parameters at 6 locations and for conventional parameters plus UV-Visible spectral absorption at 6 additional locations in the distribution system	Parameters to be monitored, instrument types, monitoring station design, and types of potential installation locations for each alternative. Approximate unit cost of each station type.
Asset	Alternative technologies for measuring chlorine residual at OWQM stations: 1. Instrument based on the DPD method, provided by Vendor 1 2. Instrument based on the DPD method, provided by Vendor 2 3. Instrument based on the amperometric method, provided by Vendor 2 4. Instrument based on solid-state technology, provided by Vendor 3 5. Instrument based on solid-state technology, provided by Vendor 4	Specific model of the online chlorine residual sensor used in each alternative. Purchase price and estimated annual operations and maintenance cost for each model.

CM = Consequence Management; CCS = Customer Complaint Surveillance; PHS = Public Health Surveillance
S&A = Sampling and Analysis; OWQM = Online Water Quality Monitoring; ESM = Enhanced Security Monitoring;
DPD = N,N-diethyl-p-phenylenediamine; UV = Ultraviolet

1.3 Guidance Overview

An overview of the framework for comparison of alternatives that will be discussed in this document is illustrated in **Figure 1-1**. This framework considers the tradeoff between benefits realized and costs incurred among the alternatives. While certain aspects of this analysis are quantitative, there are also qualitative factors to be considered, and thus some degree of value judgment is necessary to select a preferred alternative. A number of software tools are available to support application of this framework. In particular, these tools automate several of the calculations and document the analysis.

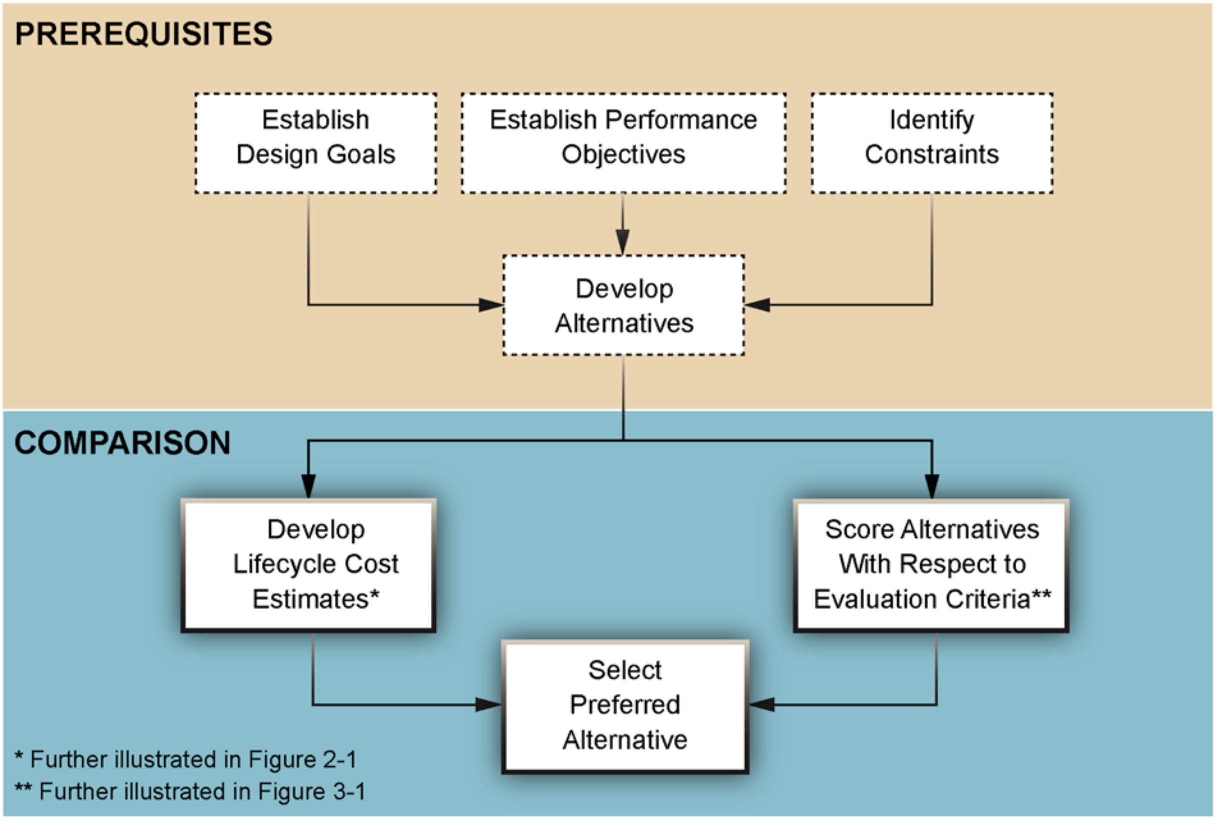

Figure 1-1. Overview of the Process for Comparing Alternatives

The process presented in this document assumes that the total possible number of alternatives under consideration has been reduced to a select set of alternatives that are viable, and that any alternatives that were obviously non-compliant with critical requirements or outside budget constraints were eliminated from further consideration.

This document is organized as follows:

- **Section 2** describes the process of developing life-cycle cost estimates.
- **Section 3** describes the process of scoring alternatives with respect to evaluation criteria.
- **Section 4** describes the process of selecting an alternative based on the lifecycle cost estimates and evaluation scores.
- **Resources** presents a comprehensive list of documents, tools and other resources cited in this document, including a summary and a link to each resource.
- **Glossary** presents definitions of terms used this document, which are indicated by bold italic font at first use in the body of the document.

Section 2: Develop Lifecycle Cost Estimates

The relative ***lifecycle costs*** of alternative SRS designs are important to consider when evaluating which alternative to select. The general terms that comprise the ***Lifecycle Cost Estimate*** (LCCE) are shown in **Equation 2-1** and defined below.

LIFECYCLE COST ESTIMATE = Implementation Costs + Operations and Maintenance Costs

+ Renewal Costs – Value of Remaining Useful Life

Equation 2-1. Lifecycle Cost Estimate Equation

- ***Implementation costs*** include all design, procurement, installation and training costs associated with implementing the system.
- ***Operations and maintenance costs*** are ongoing costs for items such as reagents, replacement parts, support contracts and the level of effort, including personnel costs, required to maintain the system.
- ***Renewal costs*** account for the cost of replacing assets that have a shorter ***useful life*** than the period chosen for analysis. In addition to procurement costs for replacement equipment, renewal costs may include the costs of redesign if the new assets differ from the original (such as a new model of water quality sensor), installation and initial training, and decommissioning and disposal of the equipment being replaced.
- ***Value of remaining useful life*** accounts for the residual value of those assets that have useful life remaining at the end of the period chosen for the analysis. Useful life is explained in more detail in Section 2.2.

Figure 2-1 expands on Figure 1-1, showing the three basic steps involved in developing the LCCE for SRS design alternatives. These steps are described in further detail in subsequent sections. An example that illustrates these steps is provided in Section 2.4.

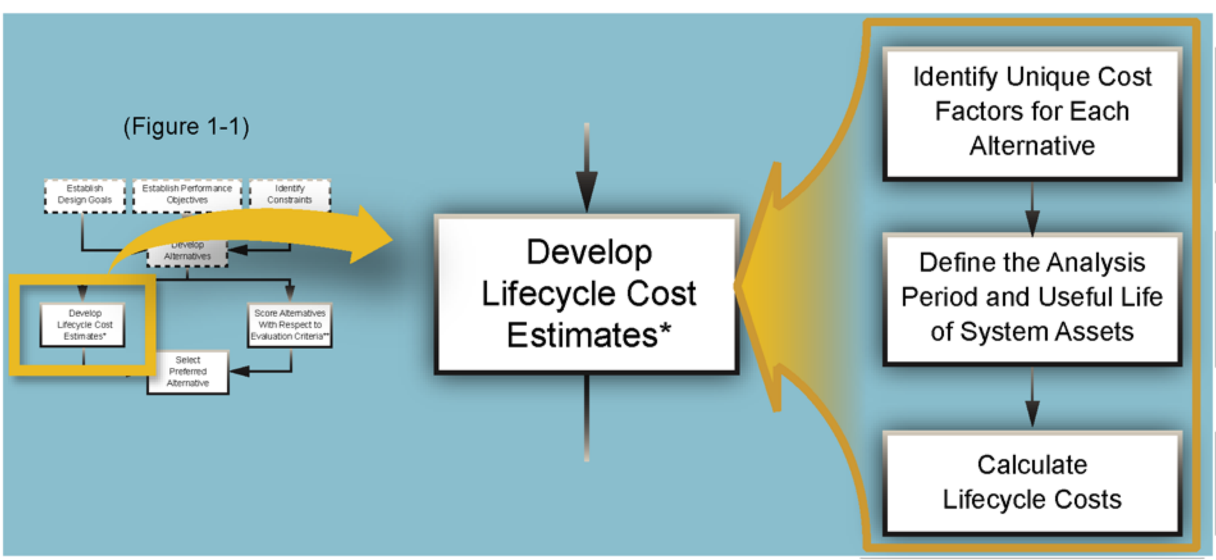

Figure 2-1. Steps for Developing a Lifecycle Cost Estimate

2.1 Identify Unique Cost Elements for Each Alternative

An LCCE is developed to a level of accuracy appropriate for the intended use of the result. In the context of the framework for comparing alternative SRS designs, the LCCE only needs to include costs that are different among the alternatives. For example, if all alternatives require procurement of the same information technology (IT) and communication equipment, the costs associated with this equipment may be excluded due to their commonality across alternatives.

When selecting cost elements to include in the LCCE, it is generally preferable to minimize the number of cost elements included to avoid unnecessary information collection and calculations. However, it is important to ensure that results are sufficiently detailed to observe meaningful differences among the alternatives. The scale of the SRS alternatives under comparison, as described in Section 1.2, will influence the cost elements that should be considered. For example, an LCCE at the system or component level may require the inclusion of design and project management costs that are not necessarily required when developing an LCCE at the asset level.

Also, only those costs large enough to make a difference within the margin of error of the estimate need to be included. The scale of the SRS alternatives under comparison (system, component or asset) will influence the necessary level of detail in the underlying data used to calculate the LCCE. In general, the level of detail required in the LCCE increases as the scale of the alternatives under comparison decreases.

The specific cost elements needed to calculate an LCCE will vary by the SRS component(s) considered in the designs. **Table 2-1** provides examples of general, high-level cost elements that might be included for each of the SRS components, as well as cost elements relevant to the entire system. Specific examples of cost elements for each SRS component are provided in Section 2.3.

Table 2-1. Example LCCE Cost Elements

	Example Cost Element	System	OWQM	ESM	CCS	PHS	CM	S&A
Implementation	Develop design documentation for the system, component or asset	X	X	X	X	X	X	X
	Develop an information management system	X	X	X	X	-	-	-
	Procure equipment	-	X	X	-	-	-	X
	Develop and implement an initial training and exercise program	-	X	X	X	X	X	X
	Coordinate with partner agencies	X	-	X		X	X	X
Operations & Maintenance	Review and analyze data and investigate alerts	-	X	X	X	X	-	-
	Maintain equipment	-	X	X	-	-	-	X
	Plan and implement training and exercises	-	X	X	X	X	X	X
	Procure software licenses	X	X	X	X	-	-	-
	Procure consumables	-	X	-	-	-	-	X
	Maintain documentation	X	X	X	X	X	X	X
Renewal	Procure replacement information technology hardware and software	X	X	X	X	-	-	-
	Procure replacement equipment	-	X	X	-	-	-	X
Remaining Useful Life	Value depreciated assets at the end of the analysis period (negative cost)	X	X	X	X	-	-	X

* Note that the four cost element categories shown in this table correspond to the terms listed in Equation 2-1.

2.2 Define the Analysis Period and Useful Life of System Assets

A common ***analysis period*** is used to develop the LCCE for each alternative considered in the comparison. The analysis period must be long enough to demonstrate the differences in the LCCE among the alternatives. However, costs become more uncertain as they are estimated further into the future, particularly given that the SRS is heavily dependent on rapidly evolving technologies such as water quality sensors and IT equipment. Thus, the analysis period should be kept as short as possible.

> **HELPFUL HINT**
>
> The analysis period is defined only for the purpose of the LCCE and is not necessarily related to the actual life of the SRS.

Selection of the analysis period should be informed by the useful life of all assets among the alternatives. ***Total useful life*** is defined in this document as the period of time that an asset is able to be economically maintained. The total useful life of an asset is determined by a number of factors including availability of replacement parts, estimated cost of repairs, performance degradation over time, and availability of improved technologies.

> **HELPFUL HINT**
>
> Set the analysis period equal to the longest total useful life among all assets used in the alternatives under comparison.

Information available to determine the total useful life of an asset includes:

- Manufacturer's documentation
- Utility experience with similar assets
- Expert or consultant knowledge about similar assets

Figure 2-2 provides an example timeline showing how the total useful life of each asset is applied over the analysis period. In this example, the alternatives being considered have four unique assets with different total useful lives. As suggested above, the analysis period is chosen as the longest total useful life across assets (which is the total useful life of Asset 3). For all assets, the lifecycle starts with the beginning of project implementation. If the end of the total useful life of an individual asset is reached within the analysis period, the asset must be replaced to maintain a fully functioning system. This replacement is termed ***renewal***, and the figure illustrates the point at which each renewal cost would be incurred. At the end of the analysis period, three of the assets have ***remaining useful life***, or additional time they can be viably operated before renewal. Both the renewal costs and the value of the remaining useful life are used in calculating the LCCE, as described in the next section.

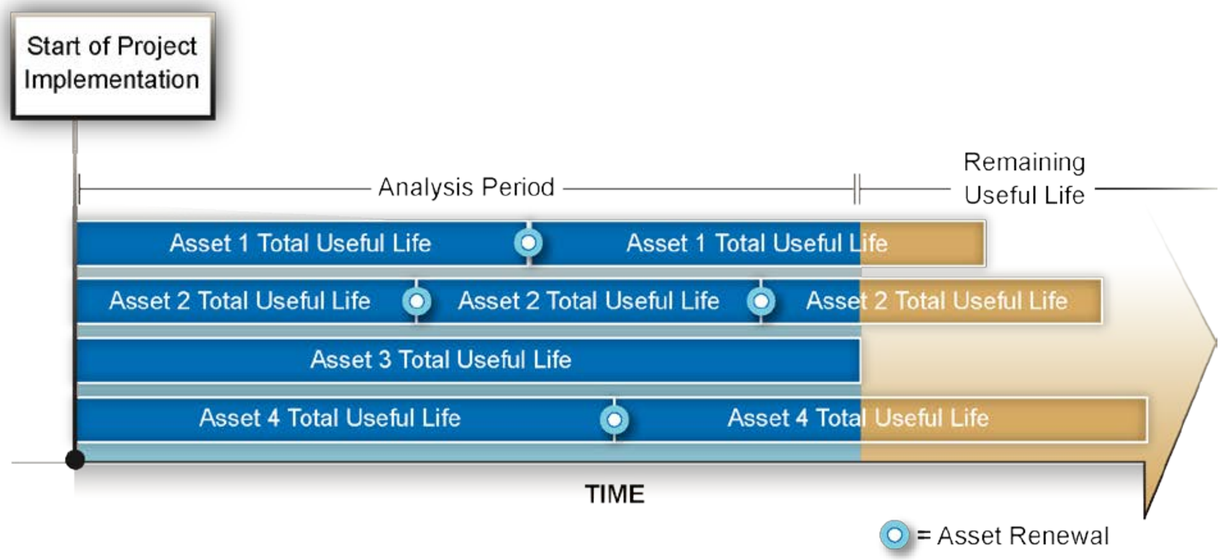

Figure 2-2. Example Timeline of Asset Renewal over an Analysis Period

2.3 Calculate Lifecycle Costs

After identifying unique cost elements for each alternative, determining the total useful lives of system assets, establishing an analysis period, and identifying necessary renewals, the lifecycle costs for each alternative can be calculated. Equation 2-1 identified the terms that comprise an LCCE, and this section describes the methods for calculating each of those terms and combining them to develop the overall LCCE.

To ensure a fair comparison, it is necessary to adjust all costs to a base year. Typically, the first year in which expenditures are incurred is selected as the base year. Costs realized in any year other than the base year are adjusted to base year dollars using an economic technique termed ***discounting***. Discounting accounts for the time-value of money, specifically that a dollar in the future is not worth the same as a dollar today due to inflation and because the money could be invested to obtain a return in the future. Methods for discounting are included below, and discounting factors can be found in the *Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis: Annual Supplement to Handbook 135*

(NIST, 2014). The 2014 edition is the latest version of this resource at the publication date of this guidance document. As this resource is updated annually, the most recent edition should be referenced to obtain discounting factors. Within this guidance document this resource will be referred to as the "latest version of the *Annual Supplement to Handbook 135* (NIST)" without a publication year identified.

The following sections describe the approach for developing an LCCE for an SRS design alternative. Each section describes the method for calculating one of the LCCE terms presented in Equation 2-1.

Throughout this document the terms used in equations (for example $C_I[Asset]$) are expressed using the following form of notation:

- *C* is used to represent a cost. *V* represents a value.
- Specific LCCE terms, as listed in Equation 2-1, are represented as subscripts such as $_I$ for implementation.
- A bracketed term is used to indicate whether the cost (or value) applies to an asset *[Asset]* or an alternative *[Alternative]*. The term *[Alternative]* denotes the summation of the cost or value for all assets used in the alternative.

Thus, $C_I[Asset]$ represents the implementation costs for an asset.

The Analysis Period is denoted as *AP* years, and the number of times an asset is renewed during the analysis period is denoted as *N*.

The Total Useful Life of an asset is denoted as *TUL*, and the Remaining Useful Life of an asset is denoted as *RUL*.

2.3.1 Implementation Costs

Potential implementation costs for an alternative include the procurement of equipment, procurement of IT hardware and software, design and documentation of the system, initial training, and all other costs associated with the initial startup. **Table 2-2** provides example implementation costs for the components of an SRS.

Utility experience with an asset is the most reliable way to estimate these costs. Costs can also be established by requesting a quotation from potential suppliers or from other utilities or organizations who have undertaken a similar project.

Calculating the implementation costs for each alternative ($C_I[Alternative]$) involves the simple summation of the relevant costs identified for the alternative. Implementation costs usually occur during the base year and therefore don't require discounting. However, if lagging implementation costs occur in later years, they need to be discounted using the approach described in Section 2.3.3.

Table 2-2. Examples of Implementation Costs

Component	Implementation Cost Example
System	• Provide management and oversight during SRS implementation • Develop and document the overall SRS design • Design and implement an information management system, possibly including a dashboard that manages and displays information for multiple components • Procure IT hardware and software
OWQM	• Procure sensors and necessary supplemental equipment such as tubing and reagents • Design, construct and install OWQM stations • Procure and implement IT hardware, software licenses and communication systems • Procure or develop a data analysis and alert notification system • Train staff on use and maintenance of installed sensors • Develop component alert investigation procedures and train staff on their roles and responsibilities
ESM	• Identify critical facilities and design a custom security monitoring system for each facility • Procure video equipment, intrusion detection systems and communication systems • Procure and implement IT hardware and software to display real-time data from intrusion detection systems and video equipment • Properly commission all security equipment • Train staff on use and maintenance of installed security hardware • Develop component alert investigation procedures and train staff on their roles and responsibilities
CCS	• Design and implement a system to collect and manage all customer feedback related to water quality concerns • Procure or develop a data analysis and alert notification system • Develop component alert investigation procedures and train staff on their roles and responsibilities
PHS	• Establish partnerships with all relevant public health jurisdictions in the drinking water system service area • Develop notification protocols in the case of a public health alert potentially related to drinking water • Implement automated alert generation and notification systems • Develop component alert investigation procedures and train staff on their roles and responsibilities
CM	• Develop consequence management and crisis communication plans • Conduct initial training on these plans • Plan and implement initial exercises to test and evaluate these plans
S&A	• Establish agreements with laboratories that could perform emergency analysis of water samples for contaminants of concern • Procure lab and field testing equipment, as necessary • Train lab and field personnel on equipment, methods and procedures • Establish baseline occurrence data for contaminants of concern

2.3.2 Operations and Maintenance Costs

Equation 2-2, is used to calculate the total operations and maintenance costs for the alternative over the analysis period ($C_{OM}[Alternative]$). Operations and maintenance costs include the labor needed to operate and maintain the system, procurement of consumables and spare parts, the recurring cost of software licenses and service agreements, the time required to investigate ***alerts***, and the time required for refresher training and document updates.

$$\mathbf{C_{OM}}[\mathbf{Alternative}] = \mathbf{C_{AnnOM}}[\mathbf{Alternative}] \times \mathbf{UPV}(\mathbf{AP})$$

Where:

C_{OM}[Alternative] = Total operations and maintenance costs for the alternative over the analysis period
C_{AnnOM}[Alternative] = Annual operations and maintenance costs for the alternative
AP = Number of years in the analysis period
UPV(AP) = Uniform Present Value factor for AP years

Equation 2-2. Total Operations and Maintenance Costs for an Alternative

C_{AnnOM}[Alternative] is the total annualized cost for all assets used in the alternative. It incorporates a common simplifying assumption that operating costs are constant for each year in the analysis period. Any operations and maintenance costs that are not already expressed on an annual basis should be annualized when calculating this value. For example, the cost of a multi-year contract can be annualized by dividing the total cost by the number of years over which the contract applies. The value for ***Uniform Present Value*** (*UPV(AP)*) can be found in Table A-2, "DOE Discount Rate," of the latest version of the *Annual Supplement to Handbook 135* (NIST).

Table 2-3 provides examples of operations and maintenance costs for SRS components. Cost quotations and literature from suppliers can be used to estimate these costs. However, the real-world operational experience from utilities or other organizations that use the same, or similar, equipment can provide a more reliable estimate.

Table 2-3. Examples of Operations and Maintenance Costs

Component	Operations and Maintenance Cost Examples
System	• Maintain the SRS information management system • Update system documentation and procedures
OWQM	• Investigate and document alerts in real time • Perform routine maintenance and calibration of sensors • Procure reagents and replacement parts as needed • Update the data analysis system and alert algorithms as necessary • Renew software licenses as necessary • Renew service contracts as necessary • Conduct annual drills and exercises on alert investigation procedures • Update alert investigation procedures as necessary
ESM	• Investigate and document alerts in real time • Perform routine maintenance and calibration on intrusion detection systems and video equipment • Renew software licenses as necessary • Renew service contracts as necessary • Conduct annual drills and exercises on alert investigation procedures • Update alert investigation procedures as necessary
CCS	• Investigate and document alerts in real time • Update the data analysis system and alert algorithms as necessary • Renew software licenses as necessary • Conduct annual drills and exercises on alert investigation procedures • Update alert investigation procedures as necessary
PHS	• Investigate and document alerts in real time • Hold routine meetings with public health partners • Conduct annual drills and exercises on alert investigation procedures • Update alert investigation procedures as necessary
CM	• Conduct annual consequence management drills and exercises in coordination with external response partners • Update the consequence management and crisis communication plans based on the outcome of drills, exercises or real-world incidents
S&A	• Perform routine maintenance and calibration of lab and field instrumentation • Procure reagents and replacement parts as needed • Perform routine sampling and analysis as needed to maintain proficiency • Renew service contracts as necessary • Conduct annual drills and exercises on sampling and analysis procedures

2.3.3 Renewal Costs

Renewal costs include the costs for updating or replacing assets that are no longer economically viable to maintain in order to continue SRS operations. Renewal may require updates to the design of the asset or the equipment and systems with which the replacement asset needs to interface. Renewal costs may also include the cost of removal and disposal of the asset being replaced. As it is difficult to predict costs that will be incurred in the future for asset renewal, a simplifying assumption often made is that the renewal cost for an asset is equal to that asset's initial implementation cost. This assumption is incorporated into **Equation 2-3**.

Renewal costs must be calculated on an asset-by-asset basis. As shown in Figure 2-2, each asset may be renewed multiple times during the analysis period. The renewal costs must be discounted separately for each renewal and then summed across the analysis period.

The total number of renewals within the analysis period is determined by dividing the analysis period by the total useful life of the asset, and rounding down to the nearest integer. If dividing the analysis period by the total useful life results in an integer, the number of renewals is the nearest lower integer (note that the initial procurement is part of implementation costs and is not accounted in the number of renewals).

Equation 2-3 shows the total cost of renewal for an alternative *(C_R[Alternative])* is the sum of the renewal costs of all assets used in the alternative that are renewed at least once during the analysis period. The total cost of renewal for a specific asset *(C_R[Asset])* is the sum of the discounted renewal cost for the asset each time it is renewed during the analysis period. As noted above, each asset's initial implementation cost (*C_I[Asset]*) is used as the cost each time the asset is renewed. The ***Single Present Value*** (*SPV*) factor is obtained from Table A-1 of the latest version of the *Annual Supplement to Handbook 135* (NIST) using the "DOE Discount rate" column.

$$\mathbf{C_R[Alternative]} = \sum^{\mathbf{All\ Assets}} \mathbf{C_R[Asset]}$$

$$\mathbf{where}: \mathbf{C_R[Asset]} = \sum^{\mathbf{1 \rightarrow N}} (\mathbf{C_I[Asset]} \times \boldsymbol{SPV(y)})$$

Where:

C_R[Alternative] = Total renewal costs for an alternative during the analysis period
C_R[Asset] = Total renewal costs for an asset over the analysis period
N = Number of times an asset is renewed over the analysis period (integer value)
C_I[Asset] = Total implementation cost for an asset
y = An integer value indicating the number of years from the first year of the analysis period that the renewal is planned
SPV(y) = Single Present Value factor for year y

Equation 2-3. Total Renewal Costs for an Alternative over the Analysis Period

Table 2-4 provides examples of renewal costs for the different components of an SRS. Renewal costs can be estimated using field experience with the equipment, manufacturer-provided data, and the recommendations of subject matter experts or consultants. Calculation of renewal costs requires the total useful life of an asset to be estimated, which is discussed in the next section.

Table 2-4. Examples of Renewal Cost

Component	Renewal Cost Examples
System	• Replace obsolete components or software used in the SRS information management system
OWQM	• Select, procure and install new sensors • Train staff to operate and maintain new sensors • Redesign or reconfigure OWQM stations where required to accommodate new sensors • Replace obsolete IT hardware or software • Dispose obsolete equipment
ESM	• Select, procure, install and commission new equipment • Train staff to operate and maintain new equipment • Replace obsolete IT hardware or software • Dispose obsolete equipment
CCS	• Replace obsolete IT hardware or software
PHS	• Generally not applicable
CM	• Generally not applicable
S&A	• Select and procure new lab and field instrumentation • Train staff to operate and maintain new instrumentation • Dispose obsolete equipment

2.3.4 Value of Remaining Useful Life

As the analysis period may not be an integer multiple of an asset's total useful life, some assets may have remaining useful life at the end of the analysis period. The value of remaining useful life accounts for the potential continued use of the assets past the end of the analysis period. Calculation of the value of remaining useful life of an asset at the end of the analysis period is performed using a straight line depreciation of the original implementation cost. As this value will occur in the future, it is subject to discounting.

The value of remaining useful life must be calculated on an asset-by-asset basis. The remaining useful life of an asset (in years) is needed to determine this value and is calculated using **Equation 2-4**.

$$\mathbf{RUL[Asset] = TUL[Asset] \times (N + 1) - AP}$$

Where:
RUL[Asset] = Remaining useful life of the asset at the end of the analysis period, in years
TUL[Asset] = Total useful life of the asset in years
N = The number of renewals in the analysis period
AP = The number of years in the analysis period

Equation 2-4. The Remaining Useful Life for an Asset

The present value of the remaining useful life for an alternative ($V_{RUL}[Alternative]$) is the sum of the value of the remaining useful life of all assets ($V_{RUL}[Asset]$) calculated using **Equation 2-5**, where $C_I[Asset]$ is the initial implementation cost for an asset and the *SPV* factor is selected from Table A-1 of the latest version of the *Annual Supplement to Handbook 135* (NIST) using the "DOE Discount rate" for the final year of the analysis period.

$$\mathbf{V_{RUL}[Alternative]} = \sum^{\mathbf{All\ Assets}} \mathbf{V_{RUL}[Asset]}$$

$$\mathbf{where}\text{:}\ \mathbf{V_{RUL}[Asset]} = \mathbf{C_I[Asset]} \times \left(\frac{\mathbf{RUL[Asset]}}{\mathbf{TUL[Asset]}}\right) \times \mathbf{SPV(AP)}$$

Where:

V_{RUL}[Alternative] = Total value of the remaining useful life for the alternative
V_{RUL}[Asset] = Value of the remaining useful life of the asset
C_I[Asset] = Initial implementation cost for the asset
RUL[Asset] = Remaining useful life of the asset at the end of the analysis period, in years
TUL[Asset] = Total useful life of the asset in years
AP = Number of years in the analysis period
SPV(AP) = Single Present Value factor for year AP

Equation 2-5. Total Value of the Remaining Useful Life for an Alternative

2.3.5 Total Lifecycle Cost

The lifecycle cost for an alternative is calculated using **Equation 2-6**, which is the summation of all the LCCE terms obtained using Equations 2-2, 2-3 and 2-5. Each term represents the total cost for the alternative and thus includes the costs incurred for all associated assets over the analysis period.

$$\mathbf{LCCE} = \mathbf{C_I[Alternative]} + \mathbf{C_{OM}[Alternative]} + \mathbf{C_R[Alternative]} - \mathbf{V_{RUL}[Alternative]}$$

Where:

LCCE = Lifecycle cost estimate for the alternative over the analysis period
C_I[Alternative] = Total implementation cost for the alternative
C_{OM}[Alternative] = Total operations and maintenance cost for the alternative over the analysis period
C_R[Alternative] = Total renewal costs incurred for the alternative over the analysis period
V_{RUL}[Alternative] = Total value of the remaining useful life for the alternative at the end of the analysis period

Equation 2-6. LCCE for an Alternative

2.4 Example Calculation of the LCCE for OWQM Design Alternatives

This example shows a hypothetical utility's application of this methodology to compare different design alternatives for OWQM. The OWQM component alternatives shown in Table 1-1 was used in this example to illustrate the LCCE methodology:

Alternative 1: Monitoring for conventional parameters (chlorine residual, pH and conductivity) at 20 locations

Alternative 2: Monitoring for conventional parameters plus UV-Visible spectral absorption at 10 locations

Alternative 3: Monitoring for conventional parameters at 12 locations and for conventional parameters plus UV-Visible spectral absorption at 3 additional locations

Alternative 4: Monitoring for conventional parameters at 6 locations and for conventional parameters plus UV-Visible spectral absorption at 6 additional locations

In this example, the trade-off between number of monitoring locations and number of parameters monitored is considered. More monitoring locations in the distribution system increases spatial coverage and provides information about a larger portion of the system. On the other hand, the addition of instruments (in this case, a UV-Visible spectral absorption instrument) to the suite of conventional parameter sensors provides more information about water quality at each location and enhances the ability of the OWQM component to detect a broad range of water quality incidents.

Table 2-5 provides a summary of the assets that are used in the four alternatives. The abbreviations listed in the second column are used in the example calculations that follow.

Table 2-5. Assets Associated with the Example Alternative Designs

Asset	Abbreviation	Number of Assets Needed for Alternative 1	Number of Assets Needed for Alternative 2	Number of Assets Needed for Alternative 3	Number of Assets Needed for Alternative 4
Sensor equipment to monitor conventional parameters	Conv	20	10	15	12
UV-Visible spectral absorption instrument	UVis	0	10	3	6
Local controller (one needed for each station)	Cont	20	10	15	12
Standard cabinet (one needed for each station monitoring for only conventional parameters)	SCab	20	0	12	6
Large cabinet (one needed for each station monitoring for conventional parameters and UVis)	LCab	0	10	3	6

Identical communication and ***information management systems*** are used for all alternatives and thus were not considered in this analysis. The costs associated with the assets that differ among the alternatives are shown in **Table 2-6**. Note that detailed cost data was rolled up to generate the summary values shown in this table.

Table 2-6. Summary of Costs for Each Asset Used in the Example

LCCE Terms	Conv	UVis	Cont	SCab	LCab
Initial implementation cost per asset	$7,000	$11,000	$8,000	$9,000	$10,000
Support contracts per year per asset	$5,000	$2,000	$1,000	$0	$0
Annual labor and consumables costs per asset	$3,000	$1,000	$0	$0	$0
Total useful life	6 Years	8 Years	10 Years	15 Years	15 Years

Fifteen years was selected as the analysis period for this example because it is the longest total useful life among the assets across all alternatives, as shown in Table 2-6. The timeline for renewal of the assets used in the four alternatives is presented graphically in **Figure 2-3**. Within the analysis period, each suite of conventional parameter sensors would have two renewal cycles (at Year 6 and Year 12), each UV-

Visible instrument would have one renewal (at Year 8), and the local controllers will have one renewal (at Year 10). The cabinets would have no renewals because their total useful life would be equal to the analysis period.

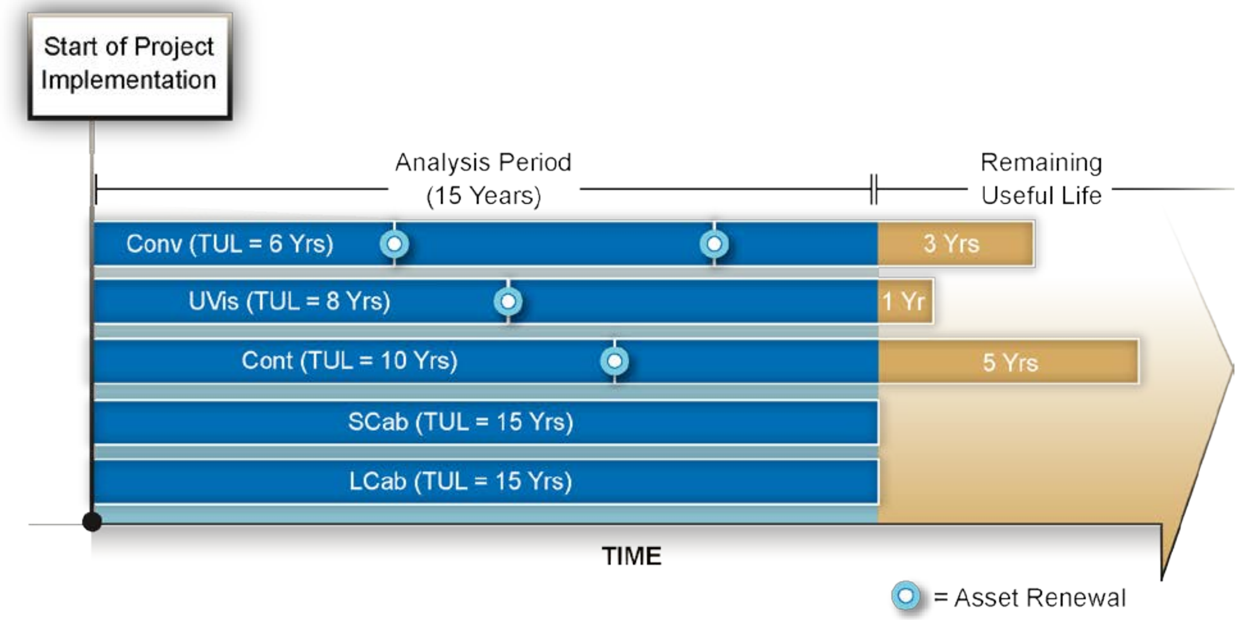

Figure 2-3. Asset Renewal Timeline for the Example LCCE

Details of the LCCE calculations for Alternative 3 are presented in the following section to illustrate the methodology. Alternative 3 was chosen for the example because it uses all five assets and thus better illustrates the nuances of the calculations. The same calculations would be carried out for the other three alternatives.

Implementation Costs for Alternative 3

The implementation costs for Alternative 3 are the sum of the implementation costs for the relevant assets, as shown below. For each asset, the number of units of the asset needed for Alternative 3 (Table 2-5) was used along with the per-unit implementation cost (Table 2-6).

$$\mathbf{C_I[Alternative\ 3]}$$
$$= (\mathbf{15} \times \mathbf{C_I[Conv]}) + (\mathbf{3} \times \mathbf{C_I[UVis]}) + (\mathbf{15} \times \mathbf{C_I[Cont]}) + (\mathbf{12} \times \mathbf{C_I[SCab]}) + (\mathbf{3} \times \mathbf{C_I[LCab]})$$

$$= (\mathbf{15} \times \$\mathbf{7,000}) + (\mathbf{3} \times \$\mathbf{11,000}) + (\mathbf{15} \times \$\mathbf{8,000}) + (\mathbf{12} \times \$\mathbf{9,000}) + (\mathbf{3} \times \$\mathbf{10,000})$$
$$= \$\mathbf{396,000}$$

Operations and Maintenance Costs for Alternative 3

Equation 2-2 was used to calculate operations and maintenance costs. The annual operations and maintenance cost for each asset ($C_{AnnOM}[Asset]$) is the sum of its yearly support contracts and annual labor and consumables costs, both identified in Table 2-6. The value for the *UPV* term (11.94) was obtained from Table A-2 of the *Annual Supplement to Handbook 135* (NIST, 2014) using the analysis period of 15 years.

$$\mathbf{C_{OM}}[\mathbf{Alternative\ 3}] = \begin{pmatrix} \mathbf{15} \times \mathbf{C_{AnnOM}}[\mathbf{Conv}] + \mathbf{3} \times \mathbf{C_{AnnOM}}[\mathbf{UVis}] + \mathbf{15} \times \mathbf{C_{AnnOM}}[\mathbf{Cont}] \\ + \mathbf{12} \times \mathbf{C_{AnnOM}}[\mathbf{SCab}] + \mathbf{3} \times \mathbf{C_{AnnOM}}[\mathbf{LCab}] \end{pmatrix} \times \mathbf{UPV}(\mathbf{15\ Yrs})$$

$$= \big((\mathbf{15} \times \$\mathbf{8,000}) + (\mathbf{3} \times \$\mathbf{3,000}) + (\mathbf{15} \times \$\mathbf{1,000}) + (\mathbf{12} \times \$\mathbf{0}) + (\mathbf{3} \times \$\mathbf{0})\big) \times \mathbf{11.94}$$
$$= \$\mathbf{1,719,360}$$

Renewal Costs for Alternative 3

Renewal costs were calculated separately for each asset and renewal for the alternative using Equation 2-3. The total number of renewals within the analysis period was determined by dividing the analysis period by the useful life of the asset, and rounding down to the nearest integer. As noted above, the sensors to measure conventional parameters would be renewed twice (at 6 and 12 years), the UV-Vis instruments renewed once (at 8 years), and the local controllers renewed once (at 10 years). The cabinets wouldn't require renewal during the analysis period and thus were not included in the calculations below.

For each renewal, the initial implementation cost for the asset (C_I*[Asset]*) identified in Table 2-6 was used as the renewal cost. The *SPV* factor was obtained from Table A-1 of the *Annual Supplement to Handbook 135* (NIST, 2014) using the number of years between the start of the project and the time of renewal. Specifically, the values for the *SPV* term are 0.837 for 6 years, 0.789 for 8 years 0.744 for 10 years and 0.701 for 12 years, all determined relative to the base year.

$$\mathbf{C_R}[\mathbf{Conv}] = (\mathbf{C_I}[\mathbf{Conv}] \times \mathbf{SPV}(\mathbf{6\ Yrs})) + (\mathbf{C_I}[\mathbf{Conv}] \times \mathbf{SPV}(\mathbf{12\ Yrs}))$$
$$= (\$\mathbf{7,000} \times \mathbf{0.837}) + (\$\mathbf{7,000} \times \mathbf{0.701})$$
$$= \$\mathbf{10,766}$$

$$\mathbf{C_R}[\mathbf{UVis}] = \mathbf{C_I}[\mathbf{UVis}] \times \mathbf{SPV}(\mathbf{8\ Yrs})$$
$$= \$\mathbf{11,000} \times \mathbf{0.789}$$
$$= \$\mathbf{8,679}$$

$$\mathbf{C_R}[\mathbf{Cont}] = \mathbf{C_I}[\mathbf{Cont}] \times \mathbf{SPV}(\mathbf{10\ Yrs})$$
$$= \$\mathbf{8,000} \times \mathbf{0.744}$$
$$= \$\mathbf{5,952}$$

$$\mathbf{C_R}[\mathbf{Alternative\ 3}] = (\mathbf{15} \times \mathbf{C_R}[\mathbf{Conv}]) + (\mathbf{3} \times \mathbf{C_R}[\mathbf{UVis}]) + (\mathbf{15} \times \mathbf{C_R}[\mathbf{Cont}])$$
$$= \$\mathbf{276,807}$$

Value of Remaining Useful Life for Alternative 3

The value of the remaining useful life was calculated for each asset using Equation 2-5. Using Equation 2-4, the *RUL* at the end of the analysis period was calculated as three years for the sensor pack (6×3-15), one year for the UV-Vis instrument (8×2-15), and five years for the local controller (10×2-15). Both cabinet types have no useful life remaining.

The remaining useful life, total useful life and initial implementation cost for each asset were used to calculate the value of the remaining useful life using Equation 2-5. The *SPV* factor used to compute the present value of these costs were found in Table A-1 of the *Annual Supplement to Handbook 135* (NIST, 2014) using the number of years in the analysis period from the base year (in this case 15 years).

$$\mathbf{V_{RUL}[Conv]} = \left(\mathbf{C_I[Conv]} \times \frac{\mathbf{RUL[Conv]}}{\mathbf{TUL[Conv]}}\right) \times \mathbf{SPV(15\ Yrs)}$$
$$= \left(\$\mathbf{7,000} \times \frac{\mathbf{3\ Yrs}}{\mathbf{6\ Yrs}}\right) \times \mathbf{0.642}$$
$$= \$\mathbf{2,247}$$

$$\mathbf{V_{RUL}[UVis]} = \left(\mathbf{C_I[UVis]} \times \frac{\mathbf{RUL[UVis]}}{\mathbf{TUL[Uvis]}}\right) \times \mathbf{SPV(15\ Yrs)}$$
$$= \left(\$\mathbf{11,000} \times \frac{\mathbf{1\ Yr}}{\mathbf{8\ Yrs}}\right) \times \mathbf{0.642}$$
$$= \$\mathbf{883}$$

$$\mathbf{V_{RUL}[Contr]} = \left(\mathbf{C_I[Cont]} \times \frac{\mathbf{RUL[Cont]}}{\mathbf{TUL[Cont]}}\right) \times \mathbf{SPV(15\ Yrs)}$$
$$= \left(\$\mathbf{8,000} \times \frac{\mathbf{5\ Yrs}}{\mathbf{10\ Yrs}}\right) \times \mathbf{0.642}$$
$$= \$\mathbf{2,568}$$

$$\mathbf{V_{RUL}[Alternative\ 3]} = (\mathbf{15} \times \mathbf{V_{RUL}[Conv]}) + (\mathbf{3} \times \mathbf{V_{RUL}[UVis]}) + (\mathbf{15} \times \mathbf{V_{RUL}[Cont]})$$
$$= \$\mathbf{74,873}$$

Lifecycle Cost Estimate for Alternative 3

The total lifecycle cost estimate for Alternative 3 was calculated using Equation 2-6 and the results from the previous steps.

$$\mathbf{LCCE} = \mathbf{C_I[Alternative\ 3]} + \mathbf{C_{OM}[Alternative\ 3]} + \mathbf{C_R[Alternative\ 3]} - \mathbf{V_{RUL}[Alternative\ 3]}$$
$$= \$\mathbf{396,000} + \$\mathbf{1,719,360} + \$\mathbf{276,807} - \$\mathbf{74,873}$$
$$= \$\mathbf{2,317,294}$$

The same computation was performed for each alternative shown in Table 2-5, and the results for all four alternatives are presented in **Table 2-7**.

Table 2-7. Summary of Costs for the Example Alternatives

LCCE Terms	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Implementation Cost	$480,000	$360,000	$396,000	$360,000
Operations and Maintenance Cost	$2,149,200	$1,432,800	$1,719,360	$1,504,440
Renewal Cost	$334,360	$253,970	$276,807	$252,690
Value of Remaining Useful Life	$96,300	$56,978	$74,873	$63,077
Lifecycle Cost Estimate	$2,867,260	$1,989,793	$2,317,294	$2,054,054

Section 3: Score Alternatives with Respect to Evaluation Criteria

When comparing SRS designs, the benefit of each alternative must be considered in addition to the LCCE. This section describes a rigorous approach for including these factors, which are generally qualitative, in the comparative analysis. The steps of this process are depicted in **Figure 3-1** and further described in the subsequent sections. An example that illustrates these steps is provided in Section 3.3.

Figure 3-1. Steps for Scoring Alternatives Using Evaluation Criteria

3.1 Establish Evaluation Framework

The first step is to establish the evaluation framework, which includes establishing the evaluation criteria, weighting each criterion and developing a scoring scale. The evaluation framework should be developed without consideration of the alternatives being compared to ensure an objective evaluation based solely on the design goals and performance objectives established for the SRS.

Evaluation criteria are generally qualitative, though quantitative metrics can be derived for some criteria. For example, tools such as hydraulic models, the Threat Ensemble Vulnerability Assessment – Sensor Placement Optimization Tool (TEVA-SPOT) (USEPA, 2010), and Water Health and Economic Analysis Tool (WHEAT) (USEPA, 2014) can be used to develop qualitative estimates of the consequences or contamination.

3.1.1 Establish Evaluation Criteria

The evaluation criteria should reflect the desired outcomes of SRS implementation and operation and provide an unbiased approach for the comparison. SRS design goals and performance objectives used to develop the set of viable alternatives can also be used to develop evaluation criteria for comparing alternative SRS designs.

For this step in the comparative analysis, it is important to clearly define the evaluation criteria. Characteristics of effective evaluation criteria include:

- *Traceable*: each criterion should directly relate to a design goal or performance objective.
- *Unique*: each criterion should be unique so that there is no "double counting" for a particular goal or objective.
- *Measurable*: each criterion should be able to be assessed, even if only qualitatively, so that a score can be assigned to each criterion for each alternative.

- *Precise*: each criterion should be specific and clearly worded such that a score can be easily assigned for each alternative without requiring interpretation by the evaluator.
- *Attainable*: the criteria should be achievable within the constraints established for the project.
- *Complete*: when considered together, the criteria should cover all SRS goals and objectives.

The number of evaluation criteria utilized should be minimized while meeting all of the characteristics identified above, in particular those of uniqueness and completeness.

3.1.2 Weight Each Criterion

The next step in the process is to develop a weighting scale and assign specific weights to the evaluation criteria established in the previous step that reflect the relative importance of each criterion. Weighting of the evaluation criteria is based on the relative importance that the utility places on each criterion, independent of the SRS design alternatives.

The weighting scale chosen should be intuitive and simple to apply. Also, it should provide enough differentiation among the criteria while not being confusing or cumbersome to apply. An example of a four-level weighting scale is shown below:

4 = *Critical*: the criterion is essential to meeting the design goals and performance objectives of the SRS.

3 = *High importance*: the criterion is important, but not essential, to meeting the design goals and performance objectives of the SRS.

2 = *Moderate importance*: the criterion helps differentiate among alternatives, but is not essential or highly important.

1 = *Low importance*: the criterion would be nice, but is not important.

3.1.3 Develop a Scoring Scale

A scoring scale needs to be developed so that each alternative can be assigned a score for each of the evaluation criteria. The scoring scale is a means of assigning numbers to criteria that are intrinsically qualitative and unlikely to lend themselves to a quantitative assessment. A scoring scale should provide enough levels to differentiate scores among the alternatives while also being straightforward to apply in a consistent manner. The score assigned to an alternative should reflect the degree to which the alternative meets the criterion. A simple four-point scoring scale follows:

3 = Completely satisfies the criterion

2 = Partially meets the criterion

1 = Minimally meets the criterion

0 = Completely deficient with respect to the criterion

> **HELPFUL HINT**
>
> Well defined evaluation criteria will ensure that scoring is intuitive. If this is not the case, it may indicate that the evaluation criteria need to be refined.

3.2 Score the Alternatives

After the evaluation framework has been developed, each alternative is independently scored against each of the evaluation criteria. Scoring should be objective and based solely on the degree to which the alternative meets the evaluation criteria. Scores should be assigned in a consistent manner across alternatives, preferably by the same individual(s) to encourage consistency.

The final score for each alternative is referred to as the ***capability score***, which characterizes how well each alternative meets the design goals and performance objectives for the SRS. It is calculated by multiplying the assigned score by the weighting factor for the individual criterion, and then summing all the weighted scores across all criteria. This can generally be completed efficiently using a simple spreadsheet. An illustrative example, without use of a spreadsheet, is provided in Section 3.3.

3.3 Example Qualitative Evaluation of OWQM Design Alternatives

To illustrate the methodology for performing a qualitative evaluation of SRS design alternatives, each step in the analysis will be shown for the OWQM design alternatives shown in Table 2-5 as a continuation of the example presented in Section 2.4.

Establish Evaluation Criteria

The following design goals and performance objectives were established by a hypothetical utility to develop the OWQM design alternatives considered in this example.

Design Goals

1. *Detect water quality incidents*: Detect unusual water quality conditions in the distribution system including regular system occurrences such as nitrification, pressure transients, rusty or turbid water, treatment process failures, pipe breaks and excessive water age. Detect foreign substances in the distribution system resulting from leaky pipes, inadvertent cross-connections, backflow incidents, chemical overfeeds during treatment and intentional contamination.
2. *Optimize application of treatment chemicals*: Provide disinfectant residual data at control points in the distribution system to better manage application of treatment chemicals and limit disinfection byproduct formation.
3. *Support compliance with water quality goals and regulations*: Identify deteriorating water quality in sufficient time to allow for corrective action that avoids potential compliance issues.
4. *Optimize investment*: Minimize the resources required to implement and operate the SRS by leveraging existing capabilities, infrastructure and personnel when practical.

Performance Objectives

1. *Spatial coverage*: Maximize the portion of the distribution system that is monitored. Spatial coverage is dependent on the number and locations of ***monitoring stations***, as incidents of abnormal water quality can only be detected if affected water flows through a monitoring station.
2. *Incident coverage*: Maximize the types of water quality incidents that can be detected. This is dependent on the parameters monitored, as an incident can be detected only if it causes a change in a monitored parameter.
3. *Alert occurrence*: Minimize the rate of ***invalid alerts*** while maintaining the ability to detect water quality incidents. Alerting is primarily impacted by the number of monitoring stations, the accuracy of OWQM data produced by the sensors and the ***data analysis*** method(s) used.
4. *Timeliness of detection*: Minimize the time required to detect a water quality incident. Timeliness of detection is dependent on the number and locations of monitoring stations as well as the frequency with which water quality data is collected and analyzed.
5. *Operational reliability*: Maximize the percentage of time that the component is fully operational. This requires proper maintenance of all equipment and information management systems.
6. *Sustainability*: Realize benefits related to day-to-day system operation as well as detection of water quality incidents that justify the cost and level of effort required to implement and operate the OWQM component.

Based on these design goals and performance objectives, the following evaluation criteria were developed. The list in the parentheses after each criterion indicates the design goal (DG) or performance objective (PO) from which the criterion was derived.

1. The ability of each station to provide data for conventional water quality parameters. (DG1, DG2, DG3, PO6)
2. The ability of each station to detect nitrification (through direct measurement of nitrate/nitrite) and turbid or discolored water to support early detection and response to frequent water quality issues. (DG1, DG2, DG3, PO2, PO6)
3. The ability of each station to detect a broad range of abnormal substances. These include contaminant classes identified by USEPA (USEPA, 2013). (DG1, DG3, P02, PO3)
4. The ability of the OWQM component to provide information about water quality throughout the distribution system. (DG1, DG3, PO1, PO4)
5. The degree to which the alternative maximizes the use of existing infrastructure. (DG4, PO6)
6. The degree to which the alternative maximizes the use of existing knowledge and training. (DG4, P05, PO6)

This set of criteria has the characteristics described in Section 3.1.1. They are traceable, unique, measurable, precise, attainable, and as a set are complete.

Weight Each Criterion

The four-point weighting scale shown in Section 3.1.2 was used for this example:

4 = *Critical*: the criterion is essential to meeting the design goals and performance objectives of the SRS.

3 = *High importance:* the criterion is important, but not essential, to meeting the design goals and performance objectives of the SRS.

2 = *Moderate importance:* the criterion helps differentiate among alternatives, but is not essential or highly important.

1 = *Low importance:* the criterion would be nice, but is not important.

Weights were assigned based on the relative importance the utility placed on the defined design goals and performance objectives and are listed in **Table 3-1**, along with the rationale for the weighting.

Table 3-1: Weights Assigned to the Example Evaluation Criteria

Evaluation Criterion	Weight	Rationale for Weighting
1. The ability of each station to provide data for conventional water quality parameters.	4	These parameters are critical for optimizing water quality in the distribution system and supporting regulatory compliance.
2. The ability of each station to detect nitrification (through direct measurement of nitrate/nitrite) and turbid or discolored water to support early detection and response to frequent water quality issues.	3	These are common water quality problems that occur in the utility's distribution system and can result in customer complaints and potential compliance issues. Though not critical, time and money could be saved by detecting these early, and it could increase customer confidence in water quality.
3. The ability of each station to detect a broad range of abnormal substances. These include contaminant classes identified by USEPA.	3	While distribution system contamination incidents are rare, their occurrence would have significant consequences for the utility and its customers.
4. The ability of the OWQM component to provide information about water quality throughout the distribution system.	4	Awareness of water quality throughout the system is the main driver of this utility's OWQM implementation. They want to better understand how water quality varies throughout the distribution system and want to maximize the ability to detect water quality incidents anywhere in the system.
5. The degree to which the alternative maximizes the use of existing infrastructure.	2	Use of existing utility facilities to house OWQM stations is preferred as it would save money and provide the utility with direct control over security and access to the monitoring stations. However, the utility is willing to install OWQM stations at non-utility owned facilities if it would better support the design goals.
6. The degree to which the alternative maximizes the use of existing knowledge and training.	2	Use of technologies that are familiar to utility staff would reduce the amount of training required to operate and maintain the component. Though of secondary importance to the day-to-day benefit the system would provide, the utility wants to minimize the burden to maximize staff buy-in of the project.

Develop a Scoring Scale and Assign Scores to Alternatives

The four-point scoring system shown in Section 3.1.3 was used for this analysis. The scoring for each of the evaluation criteria was based on the approach shown in **Table 3-2**:

3 = Completely satisfies the criterion
2 = Partially meets the criterion
1 = Minimally meets the criterion
0 = Completely deficient with respect to the criterion

Table 3-2. Scoring Logic for Example Evaluation Criteria

Evaluation Criterion	Scoring Logic
1. The ability of each station to provide data for conventional water quality parameters.	The score assigned to this criterion depends on whether conventional water quality parameters are monitored at each OWQM station: 3 = Conventional water quality parameters are monitored 0 = Conventional water quality parameters are not monitored
2. The ability of each station to directly detect nitrification (through direct measurement of nitrate/nitrite) and turbid or discolored water to support early detection and response to frequent water quality issues.	Direct monitoring to detect nitrate/nitrite, turbidity or color is necessary to satisfy this criterion. The standard sensor pack does not do this, but UV-Vis instruments do measure these parameters. Thus, the presence of a UV-Vis instrument is necessary for a station to completely satisfy this criterion. The following logic was used to score the alternatives as a whole: 3 = All stations have UV-Vis instruments (all stations completely satisfy the criterion) 2 = 50% to 99% of stations have UV-Vis instruments 1 = 1% to 49% of stations have UV-Vis instruments 0 = No stations have UV-Vis instruments
3. The ability of each station to detect a broad range of abnormal substances. These include contaminant classes identified by USEPA.	The standard sensor pack has the ability to detect some contaminants of concern and thus partially meets this criterion. The addition of UV-Vis instruments significantly increases the number of contaminants that can be detected. Thus, the presence of a UV-Vis instrument is necessary for a station to completely satisfy this criterion. The following logic was used to score the alternatives as a whole: 3= All stations have UV-Vis instruments (all stations completely satisfy the criterion) 2= Some, but not all, stations have UV-Vis instruments 1= No stations have UV-Vis instruments and thus detection is limited to substances detectable by conventional parameters 0= No detection ability (N/A for these alternatives since all stations monitor conventional parameters)
4. The ability of the OWQM component to provide information about water quality throughout the distribution system.	The score assigned to this criterion depends on the number of stations installed in the distribution system. Based on analysis using their hydraulic model, the utility determined that 20 stations are required to provide sufficient coverage and completely satisfy this criterion. The analysis also showed how coverage would be diminished with fewer stations. The results of this analysis were used to develop the following scoring logic: 3 = Twenty or more stations 2 = Eleven to nineteen stations 1 = One to ten stations 0 = No stations
5. The degree to which the alternative maximizes the use of existing infrastructure.	The utility owns ten facilities that could house OWQM stations, and thus alternatives with ten or fewer stations would completely satisfy the criterion of using existing infrastructure. Any stations beyond the initial ten will require that the utility either build new facilities to house the additional stations or install some OWQM stations in non-utility facilities. The utility used the following logic to score the alternatives: 3 = Ten or fewer stations 2 = Eleven to nineteen stations 1 = Twenty or more stations 0 = Not applicable as all alternatives will be able to use some utility facilities

Evaluation Criterion	Scoring Logic
6. Maximum use of existing knowledge and training.	In this example, the sensors used to monitor conventional parameters are familiar technology, while the UV-Vis instruments would require additional training and acquisition of new knowledge. Thus, the use of UV-Vis instruments was used as the differentiator for scoring the alternatives as follows: 3 = Use of only conventional parameters (no UV-Vis instruments) 0 = At least one UV-Vis instrument

Scores were assigned to each criterion for each alternative as shown in **Table 3-3**.

Table 3-3. Qualitative Scoring of Each Alternative

Evaluation Criterion	Alternative 1	Alternative 2	Alternative 3	Alternative 4
1. The ability of each station to provide data for conventional water quality parameters.	3	3	3	3
2. The ability of each station to directly detect nitrification (through direct measurement of nitrate/nitrite) and turbid or discolored water to support early detection and response to frequent water quality issues.	0	3	1	2
3. The ability of each station to detect a broad range of abnormal substances. These include contaminant classes identified by USEPA.	1	3	2	3
4. The ability of the OWQM component to provide information about water quality throughout the distribution system.	3	1	2	2
5. The degree to which the alternative maximizes the use of existing infrastructure.	1	3	2	2
6. Maximum use of existing knowledge and training.	3	0	0	0

Note: in this example all alternatives monitor conventional water quality parameters, so the first evaluation criterion was not a differentiator.

Calculate Capability Scores

For each alternative, the score for each evaluation criterion (from Table 3-3) was multiplied by the criterion's weighting factor (from Table 3-1) to produce a final weighted score. The final weighted scores for each alternative and criterion are presented in **Table 3-4**. The capability score for each alternative was calculated by summing the weighted scores for each criterion and is shown in the bottom row of Table 3-4.

Table 3-4. Developing a Final Capability Score for Each Alternative

Evaluation Criterion	Weight	Alternative 1	Alternative 2	Alternative 3	Alternative 4
1. The ability of each station to provide data for conventional water quality parameters.	4	12	12	12	12
2. The ability of each station to directly detect nitrification (through direct measurement of nitrate/nitrite) and turbid or discolored water to support early detection and response to frequent water quality issues.	3	0	9	3	6
3. The ability of each station to detect a broad range of abnormal substances. These include contaminant classes identified by USEPA.	3	3	9	6	9
4. The ability of the OWQM component to provide information about water quality throughout the distribution system.	4	12	4	8	8
5. The degree to which the alternative maximizes the use of existing infrastructure.	2	2	6	4	4
6. Maximum use of existing knowledge and training.	2	6	0	0	0
Capability Score		**35**	**40**	**33**	**39**

Section 4: Select the Preferred Alternative

The final step involves selection of an alternative for implementation based on the results of the steps described in Sections 2 and 3. The LCCE calculated in Section 2 provides a comparative assessment of the costs required for each alternative, while the capability scores calculated in Section 3 provide a comparative assessment of the ability of the alternatives to meet SRS design goals and performance objectives. Both of these are important to consider when selecting the SRS design to implement. This section describes methods for considering the tradeoff between cost and capability when selecting an alternative.

One outcome of this analysis may be to investigate hybrids of the alternatives identified at the beginning of the process as the results of the analysis may indicate that adjustments to the preferred alternative will provide additional capability at minimal additional cost.

4.1 Final Analysis of the Results

This section presents two analysis techniques that can facilitate comparison of alternatives based on the LCCE and capability scores calculated in the previous sections. These techniques are:

- Producing a scatterplot of the LCCE (from Section 2) against the capability score (from Section 3) for each alternative.
- Calculating and comparing the ratios of the capability score to the LCCE.

4.1.1 Scatterplots

A scatterplot can be useful for visualizing the tradeoff between costs and capability. When creating a scatterplot for this analysis, one point is created for each alternative, with the capability score plotted on the x-axis and the LCCE plotted on the y-axis.

Figure 4-1 illustrates how a scatterplot could be divided into four quadrants to provide a simple, visual differentiation among alternatives. Alternatives in the bottom right quadrant provide the best solution with the greatest capability for the lowest cost. Conversely, alternatives that fall into the top left quadrant are less desirable due to their low capabilities and high cost.

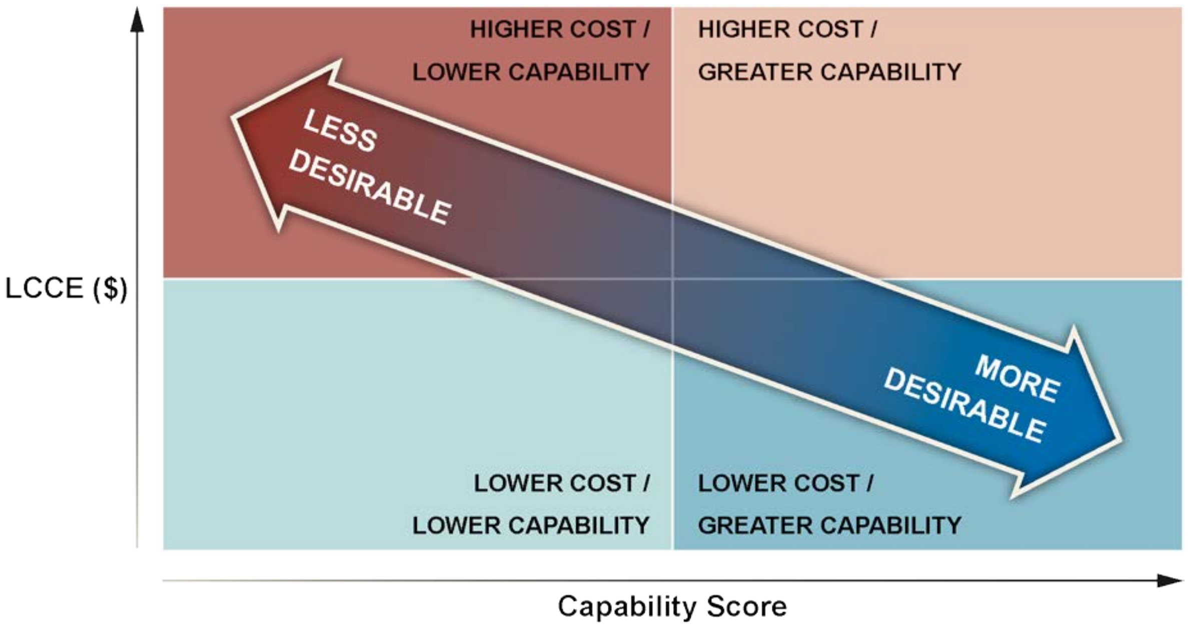

Figure 4-1. Scatterplot of LCCE vs. Capability Score

4.1.2 Cost vs. Capability Ratio

Another tool for comparison of alternatives is the cost vs. capability (C/C) ratio, which provides a numerical indication of the increase in cost for an incremental improvement in capability. It is calculated simply by dividing the LCCE by the capability score. The ratio that results is in dollars per unit of capability score. Low C/C ratios are preferable, as they indicate a lower additional cost required for a unit increase in capability score.

This type of analysis is particularly useful when evaluating alternatives that are significantly different with respect to both cost and capability. For example, if one SRS design has a significantly greater capability but at much higher cost than another alternative, comparison of the C/C ratios between these two options may provide insight into the relative cost of increased capability.

4.1.3 Interpretation of Analysis Results

The analysis tools described in this section may demonstrate that one of the alternatives is clearly superior to the others. However, it's often the case that more than one alternative provides a viable solution; multiple alternatives appear in a similar area on a scatterplot and have similar cost vs. capability ratios. In such situations, the methodology described in this document could be applied again on the subset of viable alternatives, using updated cost estimates and capability scoring where:

- Revision of the cost estimates may include replacement of order of magnitude cost estimates with more detailed estimates for cost factors with a high value, ensuring that all costs have been accounted for, and doing further research to obtain more precise values for those cost elements that differ across the alternatives being considered.
- Revision of the capability scoring may include changing the weighting and scoring for existing evaluation criteria, or addition of new criteria based on further deliberation with system designers and end users (as long as any new evaluation criteria still relate back to the DGs and POs).

4.2 Example of the Final Selection Process

To illustrate the final analysis and selection of the preferred OWQM design alternative, the methodology discussed above is illustrated for the example alternatives presented in Table 2-5, as a continuation of the examples presented in Sections 2.4 and 3.3. The results of the LCCE and final evaluation scores calculated in those sections are summarized in **Table 4-1**.

Table 4-1. LCCE and Capability Scores for the Example OWQM Design Alternatives

Alternative	LCCE	Capability Score
1	$2,867,260	**35**
2	$1,989,793	**40**
3	$2,317,294	**33**
4	$2,054,054	**39**

A scatterplot of the results presented in Table 4-1 is shown in **Figure 4-2.** This plot clearly shows that Alternative 1 and Alternative 3 can be removed from further consideration as they both provide less capability at higher cost compared with the other two alternatives.

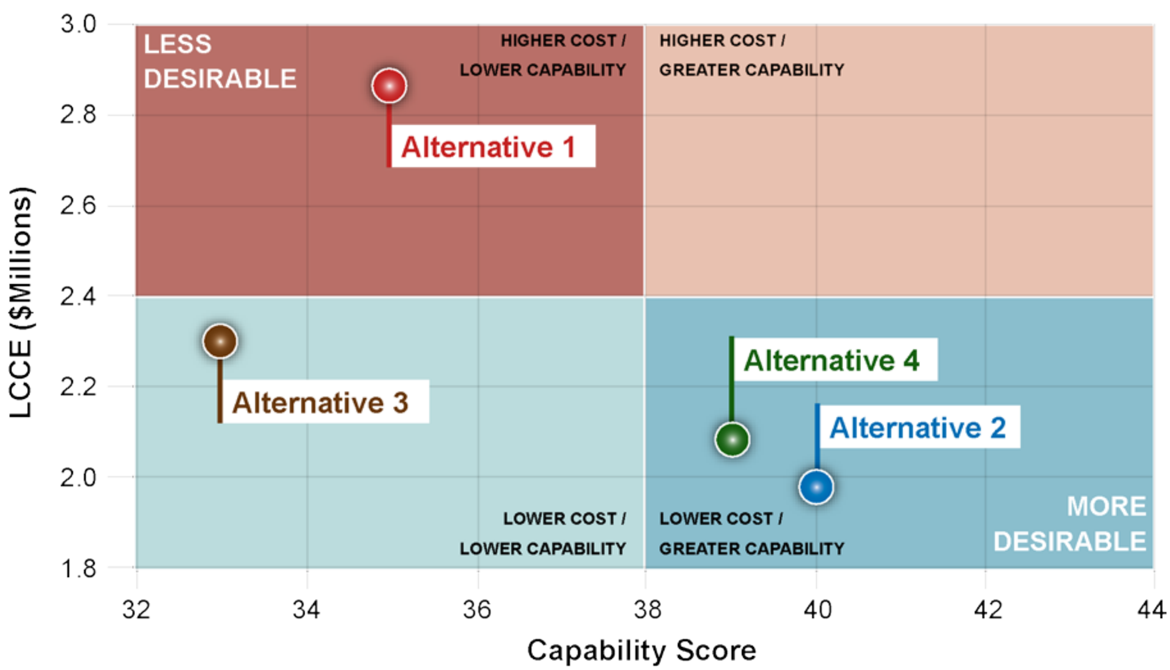

Figure 4-2. Scatterplot for Example Alternatives

Of the remaining alternatives, Alternative 2 best meets the design goals and performance objectives and has a marginally lower LCCE than Alternative 4. Alternative 2 therefore appears as the best option based on the scatterplot above, followed closely by Alternative 4.

Table 4-2 provides the C/C ratio for each of the alternatives, ordered from lowest (best) to highest (worst) C/C ratio. Again, Alternatives 1 and 3 can be eliminated from further consideration, as their C/C ratios are significantly higher than the other alternatives. Alternatives 2 and 4 have similar C/C ratios, though Alternative 4 is shown here as marginally more expensive per unit of capability score. Thus, consideration of the C/C ratio reinforces Alternative 2 as the best option for implementation, although only slightly better than Alternative 4.

Table 4-2. Capability vs. Cost Ratios for the Example OWQM Design Alternatives

Alternative	LCCE Cost	Capability Score	Cost/Capability
2	$1,989,793	**40**	**$49,745**
4	$2,054,054	**39**	**$52,668**
3	$2,317,294	**33**	**$70,221**
1	$2,867,260	**35**	**$81,922**

As noted above, there is only a marginal difference between Alternatives 2 and 4 in this example. Thus, the utility may choose to implement a more detailed cost or capability analysis between only these two alternatives. For example, Alternative 4 requires installation of equipment at facilities not belonging to the utility but Alternative 2 does not, so the utility could perform a more detailed evaluation of the additional cost and effort required for installation and operation of monitoring stations at non-utility facilities. Similarly, the weighting and scoring scale for the evaluation criteria related to the use of existing infrastructure and existing knowledge could be refined to better differentiate between Alternatives 2 and 4.

Resources

Introduction

System Engineering Principles of Water Quality Surveillance and Response System Design

http://water.epa.gov/infrastructure/watersecurity/lawsregs/initiative.cfm
This document provides information about how system engineering principles can be applied to the design and implementation of an SRS to ensure that the SRS functions as an integrated whole, and is designed effectively to perform its intended function.

Develop Life Cycle Cost Estimates

Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis: Annual Supplement to Handbook 135

http://www1.eere.energy.gov/femp/pdfs/ashb14.pdf
This supplement to Handbook 135 provides the tables with discounting factors for use in the calculation of lifecycle cost estimates.

Score Alternatives with Respect to Evaluation Criteria

Water Security Initiative: Guidance for Building Laboratory Capabilities to Respond to Drinking Water Contamination

http://nepis.epa.gov/Exe/ZyPDF.cgi/P100KLAN.PDF?Dockey=P100KLAN.PDF
This document includes a section on the capabilities which should be developed to address the contaminants of concern, and identifies and classifies those contaminants.

Sensor Network Design for Drinking Water Contamination Warning Systems: A Compendium of Research Results and Case Studies using the TEVA-SPOT

http://nepis.epa.gov/Exe/ZyPDF.cgi/P10077WZ.PDF?Dockey=P10077WZ.PDF
This document provides information on the use of TEVA-SPOT for estimating consequences of distribution system contamination and assessing the capabilities of different SRS designs for minimizing those consequences. It also includes a number of case studies demonstrating the application of TEVA-SPOT for these purposes.

Water Health and Economic Analysis Tool (WHEAT)

http://water.epa.gov/infrastructure/watersecurity/techtools/wheat.cfm (accessed April 8, 2015)
This web-site provides details and the downloadable software for the WHEAT tool. The tool provides the ability to develop scenarios and estimate the financial consequences of a distribution system contamination incident.

Glossary

alert. An indication from an SRS surveillance component that an anomaly has been detected in a datastream monitored by that component. Alerts may be visual or audible, and may initiate automatic notifications such as pager, text or e-mail messages.

analysis period. The period of time used for the LCCE analysis. It must be common across all assets and alternatives which are part of the analysis.

asset. A piece of equipment, IT system, instrument or other physical resource used in the implementation of an SRS component or system.

benefit. An outcome associated with the implementation and operation of an SRS that promotes the welfare of a utility and the community it serves. Benefits can be derived from a reduction in the consequences of a contamination incident and from improvements to routine operations.

capability score. A score which provides an indication of the degree to which an SRS, component or asset design meets evaluation criteria derived from the design goals and performance objectives established for the SRS.

component. One of the primary functional areas of an SRS. There are four surveillance components: Online Water Quality Monitoring; Enhanced Security Monitoring; Customer Complaint Surveillance; and Public Health Surveillance. There are two response components: Consequence Management and Sampling and Analysis.

Consequence Management (CM). One of the response components of an SRS. This component encompasses actions taken to plan for and respond to possible drinking water contamination incidents to minimize response and recovery timelines, and ultimately to minimize consequences to a utility and the public.

constraints. Requirements or limitations that may impact the viability of an alternative. The primary constraints for an SRS project are typically schedule, budget and policy issues (for example, zoning restrictions, IT restriction and union prohibitions).

Customer Complaint Surveillance (CCS). One of the surveillance components of an SRS. CCS monitors water quality complaint data in call or work management processes and identifies abnormally high volumes or spatial clustering of complaints that may be indicative of a contamination incident.

dashboard. A visually-oriented user interface that integrates data from multiple SRS components to provide a holistic view of distribution system water quality. The integrated display of information in a dashboard allows for more efficient and effective management of distribution system water quality, and the timely investigation of water quality incidents.

data analysis. The process of analyzing data to support routine system operation, rapid identification of water quality anomalies and generation of alert notifications.

datastream. A collection of time-series data for a specific parameter or set of parameters.

design goals (DG). The specific benefits to be realized through deployment of an SRS and each of its components. A fundamental design goal of an SRS is detecting and responding to distribution system contamination incidents. Additional design goals for an SRS are established by a utility and may relate to the operational benefits derived from SRS operations.

discounting. An accounting term that describes the technique for adjusting costs realized in the future to express them in today's value.

Enhanced Security Monitoring (ESM). One of the surveillance components of an SRS. ESM includes the equipment and procedures to detect and respond to security breaches at distribution system facilities that are vulnerable to contamination.

evaluation criteria. A set of criteria used to evaluate the capability of SRS design alternatives. The evaluation criteria are based on the design goals and performance objectives established by a utility for their SRS.

implementation costs. Costs to procure and install equipment, IT components and subsystems necessary to deploy an operational system.

information management system. The combination of hardware, software, tools and processes that collectively supports an SRS and provides users with data needed to monitor real-time system conditions. The system allows users to efficiently identify, investigate and respond to water quality anomalies.

invalid alert. An alert from an SRS surveillance component that is not due to water quality incident or public health incident.

lifecycle cost. The total cost of a system, component or asset over its useful life. Lifecycle cost includes the cost of implementation, operation & maintenance and renewal.

lifecycle cost estimate (LCCE). An estimate of the total cost of an alternative including all costs associated with implementation, operations and maintenance, and renewal. The value of the remaining useful life of any assets that have useful life at the end of the analysis period is subtracted from the LCCE.

monitoring station. A configuration of one or more water quality sensors and associated support systems, such as plumbing, electric and communications that is deployed to monitor water quality in real time at a specific location in a drinking water distribution system.

Online Water Quality Monitoring (OWQM). One of the surveillance components of an SRS. OWQM utilizes data collected from monitoring stations that are deployed at strategic locations in a distribution system. Monitored parameters can include common water quality parameters (such as, disinfectant residual, pH, specific conductance and turbidity) and advanced parameters (such as, total organic carbon and UV-Vis spectral data). Data from distribution system monitoring locations is transferred to a central location and analyzed for water quality anomalies.

operations and maintenance (O&M) costs. Expenses incurred to sustain operation of a system at an acceptable level of performance. O&M costs are typically reported on an annual basis, and include labor and other expenditures (supplies and purchased services).

performance objectives (PO). Measurable indicators of how well an SRS or its components meet established design goals.

Public Health Surveillance (PHS). One of the surveillance components of an SRS. PHS involves the analysis of public health data to identify public health incidents and investigation of such incidents to determine whether they may be due to drinking water contamination.

real-time. A mode of operation in which data describing the current state of a system is available in sufficient time for analysis and subsequent use to support assessment, control and decision functions related to the monitored system.

remaining useful life (RUL). The amount of useful life of an asset remaining at the end of the analysis period.

renewal. The replacement of an asset at the end of its useful life to maintain a fully functioning system.

renewal cost. The cost of replacing an asset at the end of its useful life to ensure that the functionality of the asset is provided until the end of the analysis period.

Sampling and Analysis (S&A). One of the response components of an SRS. S&A is activated during Consequence Management to help confirm or rule out possible water contamination through field and laboratory analyses of water samples. In addition to laboratory analyses, S&A includes all the activities associated with Site Characterization; site investigation, site safety screening, rapid field testing and sample collection. S&A continues to be active throughout remediation and recovery if contamination is confirmed.

single present value (SPV). A factor that can be used to determine how much a single, future expenditure would cost in today's dollars.

Surveillance and Response System (SRS). See Water Quality Surveillance and Response System.

total useful life (TUL). The total period of time that an asset can be economically maintained.

uniform present value (UPV). A factor that can be used to determine how much annually recurring, future expenditure would cost in today's dollars.

useful life. The period of time that an asset is able to be economically maintained. Total useful life refers to the total period of time that an asset is able to be economically maintained, and remaining useful life is the useful life of an asset remaining at the end of the analysis period.

value of remaining useful life. The value of the useful life remaining at the end of the analysis period discounted to the base year.

Water Quality Surveillance and Response System (SRS). A system that employs one or more surveillance components to monitor and manage distribution system water quality in real time. An SRS utilizes a variety of data analysis techniques to detect water quality anomalies and generate alerts. Procedures guide the investigation of alerts and the response to validated water quality incidents that might impact any aspect of operations, public health or utility infrastructure.