DECENTRALIZED WASTEWATER TREATMENT SYSTEM RELIABILITY ANALYSIS

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INTRODUCTION

Reliability analysis and life-cycle costing are used to predict the performance of a technology over time, to assess the total costs of various management strategies, and to determine the strategies that improve performance and reduce risks of failure at least cost.

In the case of the decentralized wastewater sector, very little research has been done to establish the long-term performance of onsite or cluster systems, or the effect that various management approaches may have on that performance. These approaches could include, for example, high quality design and equipment requirements; preventive maintenance, repair, or replacement; residuals management needs; inspections; remote monitoring; education and training of installers, operators, inspectors and maintenance specialists; certification and licensing for all practitioners; and homeowner education. With greater understanding of reliability analysis and life-cycle costing, the potential exists for substantial improvement in the performance and cost-effectiveness of the decentralized wastewater sector.

The National Decentralized Water Resources Capacity Development Project (NDWRCDP) initiated the project “Decentralized Wastewater System Reliability Analysis” as an integral part

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of long-term efforts to improve our understanding and to strengthen the foundations of training and practice in the field of onsite/decentralized wastewater treatment. The final deliverable of this project is a handbook (http://www.ndwrcdp.org/userfiles/WUHT0357.pdf) useful to public and private agencies, utilities, decentralized service providers, and regulatory and policy workers who wish to manage decentralized wastewater treatment systems more efficiently.

This paper gives an overview of the project and goes into detail about how four of the tools that have been identified could be used in reliability studies of decentralized wastewater treatment.

OVERVIEW OF THE PROJECT

Decentralized systems are a permanent part of the wastewater infrastructure. Understanding how to improve the performance of these systems is crucial to allocating the often scarce resources available for hardware and management. *Asset management* is one tool to use in deciding how to allocate those resources. While using an asset management framework for centralized wastewater system management has become common in some countries, asset management has not been typically used in the decentralized field.

The two main barriers to using asset management in the decentralized field are the lack of information about the reliability of decentralized wastewater systems and components and the lack of capacity to evaluate that performance against engineering, ecological, public health, and socioeconomic goals. Removing these barriers would help people to use asset management to evaluate the effects of different management approaches and to choose the least-cost way of meeting performance goals.

The critical elements of this project are developing a framework through which a practitioner may select appropriate asset management and reliability assessment tools and then understanding the tools available to practitioners.

The Framework

The purpose of the framework is to provide an overarching process to guide andbook users to the tools best suited to help them manage the reliability and cost of their particular decentralized wastewater treatment system(s). The framework guides users through a step-by-step process, alerting them to the different issues they will need to consider and directing them to an appropriate set of tools relevant to their situation. These tools will assist users in optimal management of the assets and the risks associated with decentralized wastewater treatment.

The framework provides a generic process applicable to most situations, though three points need to be made to qualify this statement. First, real-life situations do not always occur in simple logical steps, and some aspects of the process may already be finished when a user picks up the handbook. Despite this, a user will be able to use the framework to identify the missing parts of the process that will help accomplish best management of the reliability and cost of the system(s) in question. Second, iteration of some steps may be required before further steps can be completed. Third, different tools will be applicable at different US EPA Management model levels, and some tools will be applicable differently depending on the US EPA Management level.

The Tools, Methods, and Models

With the framework in place, one method of thinking through the inputs and choices has been provided at a broader level. To implement the principles of asset management, the decentralized wastewater industry requires a specific set of tools, methods, and models to help a decision maker gain the appropriate information to improve decision-making. This project has identified three broad sets of tool types that will be necessary in certain cases.

The focus of this project has been on reliability and costing tools, with less effort applied to information management tools. To date, a large suite of tools that may be applicable to the decentralized wastewater industry has been identified. A subset of these tools has been developed in detail for the handbook, providing the target audience(s) with information necessary to determine whether the tool is a good choice for their situation. Tools such as life-cycle costing, risk-cost method, activity-based costing, failure curve determination, critical component analysis, fault tree analysis, use of geographic information systems, (GIS), and cohort analysis have been considered. Additionally, the handbook uses a case study and real-life examples to highlight places where the tools have been used or what impact their use may have had, if they had been used.

The Handbook
The handbook provides a wide range of potential users with information regarding the use of asset management techniques, how to apply the framework, what tools exist for their use, examples of others who have blazed the path ahead of them, and other research and data requirements that are recommended for future efforts.

Intended audience(s)
The work of this project is intended to have application for a wide range of audiences. How the information, tools, and framework are used will vary by each audience depending on their needs. Practitioners, regulators, responsible management entities (RMEs) for decentralized systems, and policy makers make up the predominant possible users, though some manufacturers may also be interested. The homeowner may be the ultimate beneficiary of better decision-making by having the most reliable and cost-effective wastewater treatment and management option available to them.

Practitioners and RMEs would likely use specific tools in the handbook to achieve their intended outcome, be it greater cost effectiveness, less maintenance requirements due to greater reliability, or some combination of both. Regulators, policy makers, and some RMEs would likely be interested more in the framework and in the tools that consider cost and reliability issues more broadly, though they may also be interested in some very specific tools to address current issues of concern to their jurisdictions.

Data needed to use the tool(s) and costs of using the tool(s)
Data needs for application of the tools of this project vary widely. In some cases, the data exist and are quite simple to acquire, while in others little to no data exist, so the data will need to be acquired for successful application of the tool. Similarly, the cost of implementing these tools will vary. In many cases, the cost of using the tools will be limited to the time it takes for a person to learn how to use them. In others, data acquisition, information management systems necessary to manage the data, and assistance interpreting the data will be required.

A FRAMEWORK FOR ASSET AND RISK MANAGEMENT
The framework (Figure 1) was synthesized from a review of literature and practice in the fields of asset management, reliability and risk assessment/management and decentralized wastewater management. The framework was designed to parallel existing asset management initiatives in

the centralized field. However, the relative complexity of multiple stakeholders and diverse risks in decentralized wastewater management requires significant adaptation in how it is applied. Reliability and cost tools are only relevant to asset management of decentralized systems within a context that recognizes when, where, and how these tools are needed. The framework attempts to provide that context.

The framework incorporates aspects of asset management and risk assessment, and it reflects:

- A step-by-step process for the user which may be applied through one or more iterations;
- The central place of the information system, which is added to and accessed in the different steps of the process as needed; and
- The key role of communication with stakeholders, which is important for almost all steps of the process

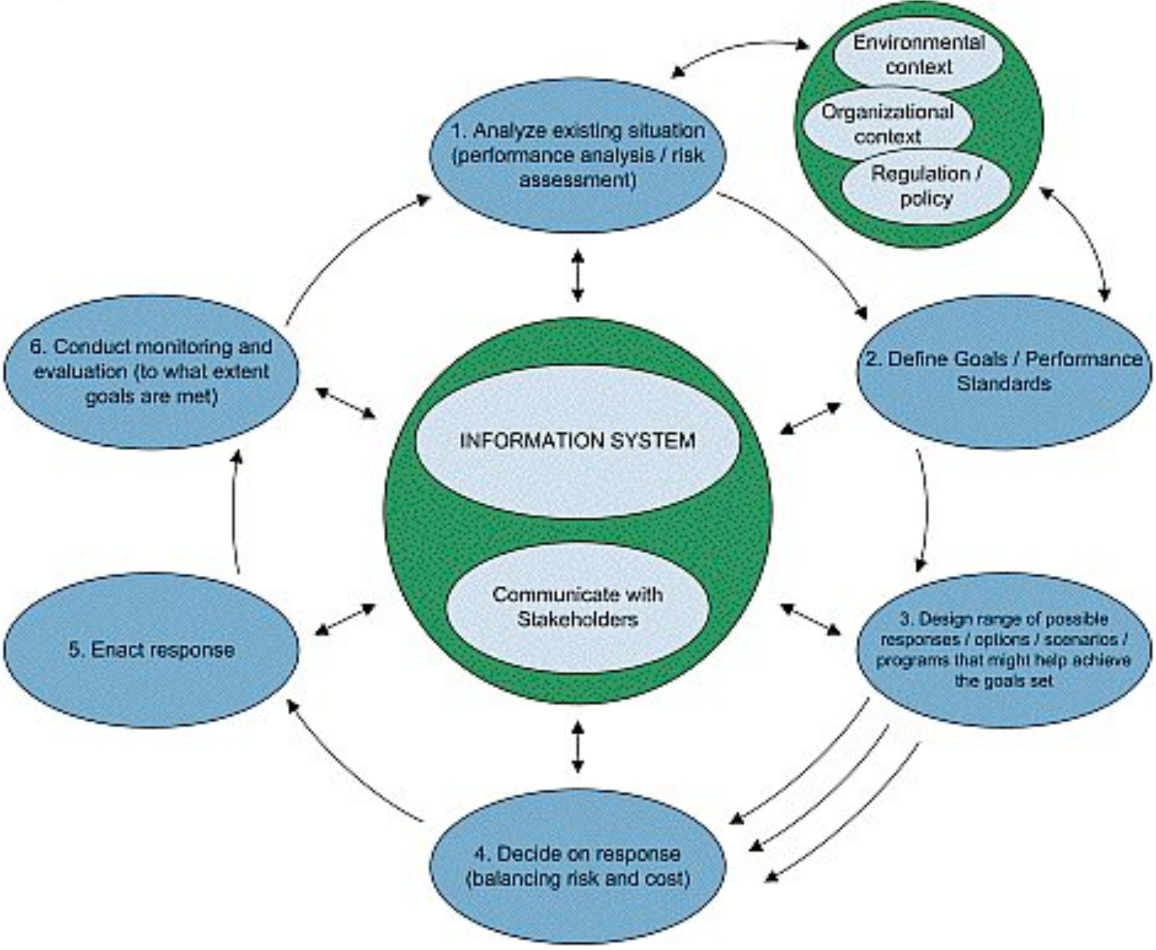

Figure 1 Generic Asset and Risk Management for Decentralized Wastewater Treatment Systems

Elements in the framework

Two elements are central to all the steps in the framework: information systems and communication with stakeholders. There are three contextual elements that influence the early steps in the framework: the biophysical environment, the organization, and the regulatory and policy context. These central and contextual elements are described in detail below.

Information system

The information system is a database that includes information such as

- An asset inventory (system type, age, location, capacity/scale/design flow, maintenance history),
- Ongoing performance information (site condition assessments, monitoring, loading rates),
- Biophysical information (planning/land use, lot size/density soil, wetness, slope, water courses, vegetation, watershed properties),
- Data on expected reliability of systems and components, and
- Cost data for capital works and operations (historical cost of capital and operations and maintenance).

Communication with stakeholders

The disaggregated nature of decentralized systems presents challenges because many different parties are involved in their use and operation. Designers, manufacturers, homeowners, installers, managers, inspectors, and regulators all play a role. In addition, since impacts from such systems directly affect other parties such as neighbors or other community members, the circle of stakeholders for such systems further widens. The explicit mention of communication with stakeholders in the framework highlights the need for communication at virtually all steps of the asset management process.

Environmental context

The natural environment places constraints on the type of decentralized system that may be safely operated in a particular region. Thus environmental factors must be entered into the information system and considered in the initial steps of situation analysis and definition of goals and performance standards.

Organizational context

The organizational structure plays a significant part in defining how and by whom the risks and costs of decentralized systems are borne. It therefore provides a context for the analysis of the existing situation and the definition of goals. The US EPA management level somewhat describes this context; however, individual situations may have peculiarities regarding ownership and control that need to be captured in this element of the framework.

Regulatory and policy context

The regulatory and policy context includes requirements for individual systems and watershed-wide guidelines that need to be taken into account.

Framework Steps and Tools

Here is how the framework can be applied, with a step-by-step guide.

Step 1. Analyze existing situation – performance analysis/risk assessment

In this step, the situation is assessed, including environmental constraints, the regulatory and policy context, the organizational context, and inventory of the decentralized systems as they are currently operating. This assessment pinpoints the particular risks and constraints of the given situation in order to use them in defining appropriate goals and performance standards.

The risks to be considered in this assessment are engineering and reliability, ecological, public health, and socio-economic risks at both the micro (immediate vicinity of a system or set of systems) and macro (watershed or region) scales. Quantitative or qualitative procedures will be necessary depending on the situation and the level of data available. The information system is used to determine the current and projected future performance of the systems under the current user/operational practice. This step assesses the status quo, identifies the needs, and sets the stage for defining appropriate goals.

Step 2. Define goals/performance standards

The goals and performance standards are based on the findings of the assessment, made in Step 1 above, and take into account the environmental constraints, the regulatory and policy context, the organizational context, the current and projected performance of the systems, and the views of stakeholders. Agreement needs to be reached with stakeholders on performance standards for watersheds and customer service in the areas of engineering, environment, public health, and socio-economic factors. The goals and performance standards may need to be made at various levels, including the individual wastewater treatment system, a set of systems (defined, for example, by location or time of construction), management organization, and/or other levels related to society and environment.

Step 3. Design a range of possible responses/options/scenarios/programs

In this step, different possible ways to reach the desired goals and performance standards are articulated and explored. Benefits and costs of each are described. Consultant input is generally used for this step.

Step 4. Decide on response (balancing risk and cost)

This step might also be called options assessment. The aim is to make a decision between the different options articulated in Step 3. It will involve modeling the effects of the options, cost modeling (including life-cycle costing) of different options, and assessment against the desired goals/performance standards. It may also involve integrated risk management (considering all different types of risks concurrently), organizational risk management, and/or socio-economic risk assessment. It may involve stakeholders in evaluating the proposed options against the goals/performance standards, since simple answers may not be apparent and different parties are likely to have different views on relative importance of various issues.

Step 5. Enact chosen response

At the time of deciding on a response, criteria need to be set at both the system and organizational level for the monitoring necessary to determine the performance level of systems and potential impacts. An evaluation against the goals/performance standards also needs to be planned.

Step 6. Conduct monitoring and evaluation

Step 6 requires inventory analysis, information management, impact assessment, life-cycle costing, and engineering/technical reliability tools

RELIABILITY ASSESSMENT TOOLS

For the purposes of this project, reliability of a wastewater treatment system is defined as “the probability of adequate performance for a specified period of time under specified conditions or...the percent of the time that effluent concentrations meet specified permit requirements" (Metcalf & Eddy 2003).

In this section, we give an overview of the reliability tools to be used in the project, establish the performance standards to be used as examples in this project and describe two tools that could be used to analyze whether systems are meeting those standards.

Overview of Reliability Tools to be Used in the Handbook

A series of questions was produced to capture the uses that different stakeholders would have for reliability tools. Table 1 presents the tools used in the handbook.

Two of these tools, actuarial studies producing failure curves and process reliability, are presented in some detail in this section. Others are described briefly later in this paper.

Performance Standards

A fundamental part of choosing reliability tools and data sources is deciding what type of reliability is to be assessed. Enumerating a system's performance standards from the perspective of all stakeholders is a painstaking exercise; one reliability system expert (Moubray 1997) says "this step alone usually takes up about a third of the time." For the purposes of illustrating reliability tools in this project, we have chosen only two high-level performance standards with different properties.

- Adequate hydraulic dispersal of the effluent, defined by absence of effluent on the surface of the soil absorption system (SAS). This or a similar performance standard is found in many jurisdictions. Whether or not the wastewater treatment system is meeting the standard at any given time is readily observable. On the other hand, meeting the standard does not guarantee adequate treatment. And unless there are observation ports in the SAS, it takes more complicated measures than repeated visits to determine whether a system is complying with the standard by a large or small amount—that is, whether the effluent is or has been *near* the surface of the SAS or not.
- Nitrogen content in the effluent of ≤ 20 g N_{tot}/L, before the soil absorption system. There are many jurisdictions where a nitrogen standard is applied; we have arbitrarily chosen a particular nitrogen standard for the sake of discussion. This performance standard differs in several ways from the hydraulic dispersal standard. Simple inspection is insufficient to determine whether the standard is being met or not at a given time; sampling and laboratory tests are required. Meeting the nitrogen standard does guarantee adequate treatment, at least for nitrogen at the time of the sampling event and upstream from the sampling point. Finally, sampling and testing once is enough to determine whether the system is meeting the standard by a large or small margin (at the time of the sampling), and a series of repeated sampling and testing gives a view of the variability in system performance over time.

Table 1. Reliability and costing tools included in the handbook, and which stakeholders would find them most useful.

Tool	Useful to		
	Practitioner[1]	**Responsible Management Entity (RME)**	**Regulator**
Reliability tools			
Actuarial studies producing failure curves	X	X	X
Cohort analysis	X	X	X
Process reliability	X	X	X
Failure modes and effects analysis		X	X
GIS-based tools		X	X
Probability assessments[2]	*X*	*X*	*X*
Critical component analysis	*X*	*X*	*X*
Statistical field sampling of system performance			*X*
Systematic troubleshooting	*X*	*X*	*X*
Costing tools			
Life-cycle costing (LCC) / Cost effectiveness analysis (CEA)	X	X	X
Activity-based costing (ABC)	X	X	
Risk-cost modeling	X	X	X
Analysis of asset cost inventories and databases	*X*	*X*	
Economic life replacement analysis	*X*	*X*	
Cost benefit analysis (CBA)		*X*	*X*
Integrated resource planning (IRP) framework		*X*	*X*
Cost perspective tests		*X*	*X*

[1] Practitioner here refers to designers, installers, operators, and maintainers
[2] Italicized tools are described briefly in an appendix.

Many other performance standards might be chosen. A far-from-exhaustive list of other performance standards, both quantitative and qualitative, for decentralized wastewater treatment systems includes:

- Total phosphorus levels in effluent leaving the system ≤ 0.5 mg/L
- $CBOD_5$ (carbonaceous biological oxygen demand) levels in effluent ≤ 25 mg/L
- TSS (total suspended solids) levels in effluent ≤ 25 mg/L
- FOG (fats, oils, and grease) levels in effluent ≤ 25 mg/L
- Fecal coliforms levels at 0 CFUs/100 ml (e.g., for surface discharge)
- Life cycle cost is less than or equal to that of a centralized system for the same area
- 75% of total phosphorus is recycled to agricultural use
- The septic tank is water-tight, both with respect to leaks in and out below the fill line and leaks in of water from above
- Effluent is distributed evenly to all trenches in the SAS
- Use of fossil fuels and other natural resources is kept low
- System owner and others are exposed to little or no bad odors or unpleasant sounds
- The system is easy to use
- The system functions well even with significant weekly or seasonal variations in flows and/or wastewater constituents
- The system does not spill untreated wastewater into the basement
- The system fits into the landscape in a way the owner and neighbors find aesthetically pleasing

Actuarial Studies Producing Failure Curves

Failure curves illustrate the number of units (systems or components) in a population, which are failing at any given time of the lifetime of that population. Once the basic attributes of the failure curves are established, then mean time before failure (MTBF) and many other potentially useful metrics can easily be calculated.

Insights into both performance standards discussed in this project, the surfacing of effluent and compliance with the nitrogen removal standard, may be gained by analyzing the failure curves.

Failure curves are plotted by analyzing actuarial data, that is, data from past failures. The data required for each failure include, at a minimum, information on when the unit was installed, when it was found to be failed (if ever), and when it was last known to be performing adequately.

Much other information about the unit could also be important. The supplementary information helps define the cohort of units to be analyzed. For example, Hudson (1986) argues that knowing the place and date of system construction (and therefore the regulations under which the system was designed and constructed), plus the soil type on which the system is installed, gives ample predictive power for failure rates. Since 1986, a greater variety of treatment systems have been used. Nonetheless, a more recent study (CT Consultants 2001) found that in northeast Ohio, the following characteristics of system type did not play a significant role in performance: aerobic treatment vs. septic tank only, or presence or lack of an effluent filter on the septic tank. Still, if detailed information such as system type, name of designer, name of installer, frequency of maintenance (including septic tank pumpouts), etc. is associated with the other data on each system, then it becomes possible to perform analyses to find out whether each factor has a significant effect on performance.

Detailed information on the mode of failure is useful, but not necessary, in failure curve analysis. For example, is effluent surfacing because the entire SAS is clogged or because the distribution box is tilted and only part of the SAS is being used? With information like this, more nuanced pictures of the patterns of failure can be drawn, and it becomes easier to make decisions about types of intervention that could reduce failure rates.

Without information on mode of failure, failure curve analysis still have many uses. For example, failure curves can be used to decide how often a system manager will inspect a system to see whether failure has occurred—regardless of the failure's cause.

Possible shapes of failure curves

Examples of failure rate distributions over time for systems or system components are given in Figure 2. The discussion of the different curves and their implications for maintenance procedures is taken from Moubray (1997).

In all these failure curves, the X-axis is time and the Y-axis represents the *conditional probability of failure*. The conditional probability of failure is defined as the probability that a member of the population at the beginning of a time period (e.g., a year) will fail by the end of that time period.

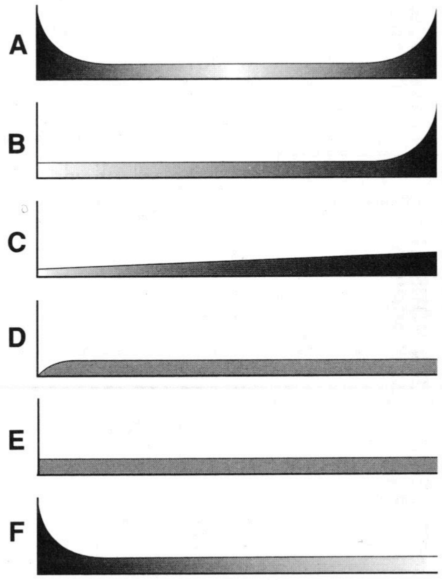

Figure 2. Six Patterns of Failure. Source: Moubray (1997).

Pattern A, the so-called bathtub curve, shows a relatively high number of failures in the beginning of a unit's life (sometimes called the period of infant mortality), followed by a period of approximately constant failure, followed by a wear-out time. This curve is a combination of at least two failure modes—one which brings about the infant mortality, and one displayed at the wear-out phase. Maintenance implications are discussed in connection with Patterns B and F, below.

Pattern B applies to units which fail in relatively small numbers over a useful life, after which the failure rate rapidly increases. Establishing the useful life for a unit is done by gathering enough actuarial data to plot a curve like Pattern B. Maintenance procedures will vary, depending on cost of detecting failure, consequences of failure, and costs of overhaul or replacement. For those units with high consequences of failure, the key datum for scheduling maintenance tasks is the length of the useful life.

Pattern C has a steadily increasing probability of failure, without any clear end of useful life. It can be associated with material fatigue. The slope, which can vary from nearly flat to rather steep, will have a strong influence on the maintenance strategy chosen.

Pattern D is similar to Pattern C, except that there is a brief period of very low probability of failure early in the unit life.

Pattern E shows a constant rate of failure over time. The distribution of failure over time suggests no critical time for maintenance interventions. In fact, in many industries, maintenance has been documented as the *cause* of many failures. Reduced maintenance of components which show pattern E may reduce failure rates.

Pattern F is the beginning of the bathtub curve, without the wear-out period at the end. A high infant mortality is followed by constant or gradually increasing failure probability. In the civil aircraft industry, studies have shown that more than two thirds of the units follow this failure pattern (Moubray 1997). Reactive maintenance is usually the most efficient way to address infant mortality failures. Closely analyzing a unit from a reliability perspective before it is used can also prevent some infant mortality.

The shape of the failure curve helps determine which further metrics can give important information. Mean time before failure (MTBF) is a commonly discussed metric. This metric can give significant information about the expected lifetime of a unit which exhibits failure curve patterns A or B. Consequently, the units can be targeted for some sort of intervention (replacement, more frequent inspections, or some other measure) at the time when the populations start wearing out. For units conforming to the other patterns, which have no distinct time that they start wearing out, MTBF does not give meaningful information about when to accelerate interventions.

Establishing the shape of a failure curve

Hudson (1986) gives a simple way to determine the shape of the failure curve. His study is of systems with surfacing effluent, but the principles are broadly transferable. The null hypothesis is that the systems exhibit failure curve pattern E, a constant failure rate over time. In a hypothetical example, Hudson tests whether the failure rate is steeper in the first three years of system life than over the next three years, that is, whether the systems exhibit patterns A or F. The test is performed by comparing the failure rates in the two time periods and using the Student t-test to see whether the difference is statistically significant.

Given a large amount of data, the data can simply be plotted with conditional probability of failure vs. time. However, simple inspection of the data may be insufficient to determine the shape of the curve. Multiple hypotheses about which parts of the curve are steeper may need to be tested to come up with the “true” shape.

Process Reliability: A graphical tool and a statistical tool

The effectiveness of treatment processes varies, because of variations in influent flow, temperature, and constituents; variations in performance of mechanical equipment; variations in biological processes, and other factors. The variation in performance of wastewater treatment processes using biological systems can frequently be described with a log-normal distribution. When this is the case, a statistical (coefficient of reliability) or a graphical tool can be used to find the mean design value that will allow the system to achieve a certain level of treatment X% of the time. The graphical tool can also be used to display the variation in results in a way that makes the level of reliability transparent.

These tools can be used for both the nitrogen performance standard and the performance standard forbidding surfacing of effluent. We will discuss first how the graphical tool can be used with data that vary over a range, and then explain how to apply them to binary data such as whether effluent is surfacing or not.

The graphical tool is easiest to explain. Consider flow rates of effluent measured throughout the day in one, five, or sixty-one homes (Figure 3). Displaying hourly flow rate vs. time of day gives

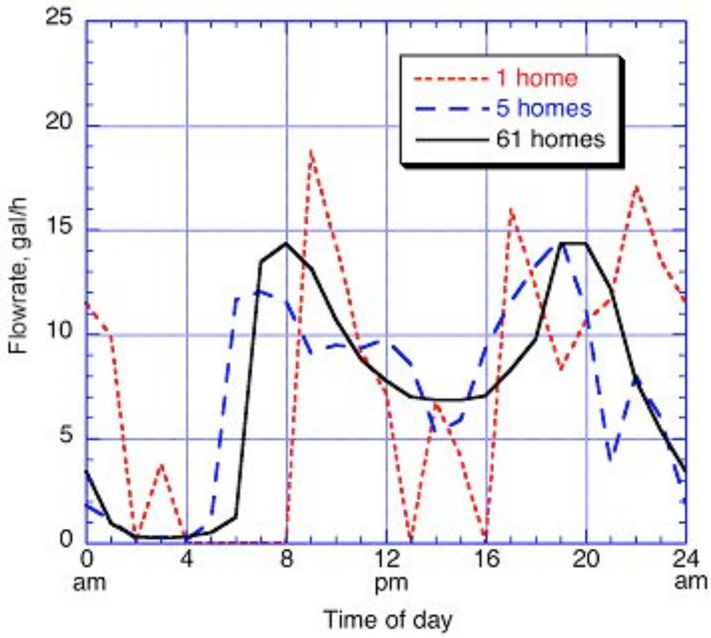

Figure 3. Hourly Flow Rates Measured Over a 24-hour Period.

a good picture of when the variations take place, and it is easy to guess what types of water uses might be contributing to the flows at different times of day. However, the figure does not give a clear sense about how often various hourly flow rates occur. If your task is to design a wastewater system that can handle variations in the hourly flow rate, then a more useful display is found in Figure 4.

In Figure 3, the X-axis has been transformed to be the log of the percent of values which are at or under the given flow rate. For all three sets of homes, for example, 50% of hourly flows are at or under 12.5 or 13.0 gallons per hour. From inspecting the line with short dashes in Figure 4 it can be seen that a system designed for one home designed to handle a maximum hourly flow of 17 gallons would be 95% reliable. That is, for 95% of the hours measured, the flow rate would be at or under the maximum the system was designed to handle. To achieve 99% reliability, a design value of 21-22 gallons per hour would be necessary (estimated, since the line goes off the graph). In practice, of course, the system would be designed for a maximum daily flow, or even flow over a couple days, but the principles of the analysis are the same.

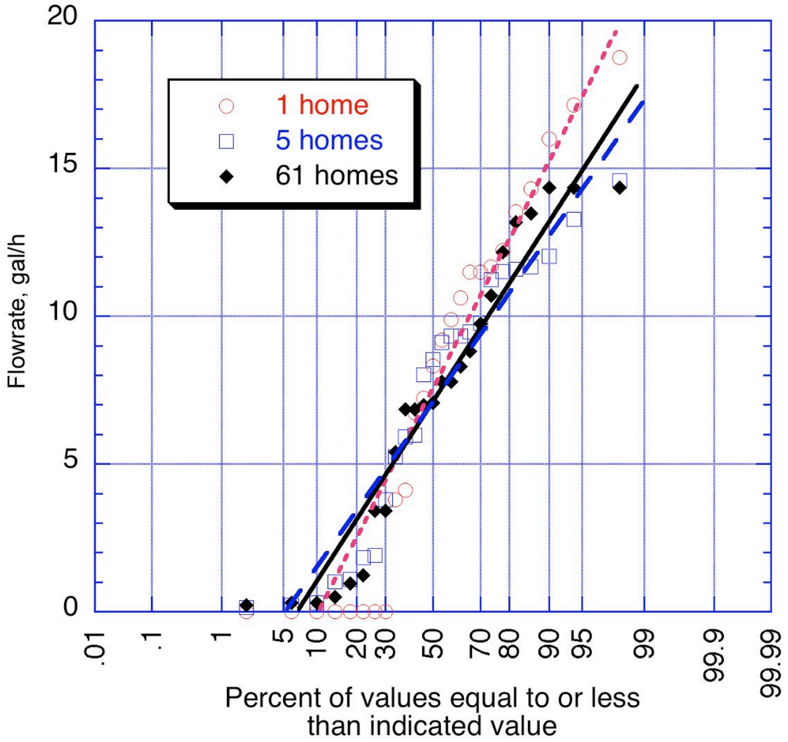

Figure 4. Hourly Flow Rates vs. Percent of All Values Less Than or Equal To That Flow Rate.

For data sets where N (number of data points) is large or very large, then the graphical method is not necessary. In a spreadsheet format, the data can be arranged in order of value and the value at any given percentile can be found directly. There are several advantages to displaying the data graphically where N is not large. First, for data distributed log-normally, the log scale of the percent on the X-axis allows a straight line to be drawn through the data. In Figure 4, the straight line for the 1-house data (short dashes) can visually be extrapolated to 99% or 99.9%, even though there are only 24 data points. Plotting the data also allows the eye to see trends that might be missed in blind application of a formula. In Figure 4, the solid line for the 61-home data set shows that 99.9% of all hourly flows are 18 gallons/hour or less. Looking at the data themselves, however, it seems that the trend might not be a straight line from the 70% mark and to the right: rather, the hourly flows seem to approach a limit closer to 15 gallons/hour. Before investing a lot in a solution capable of handling higher hourly flows, the designer might want to gather more data to see whether 15 gallons/hour might give 99.9% or greater reliability.

Whether N is small or very large, the graphical display of the data makes it easy to understand the importance of the slope of the straight line fitted to the data points. If dollar costs of achieving a given level of treatment (or, in this case, of handling a given flow) are displayed directly on the Y-axis, then it can be easy to appreciate how much extra it costs to achieve each higher level of reliability.

The graphical approach can also be used to find the design mean necessary in order to achieve a certain level of reliability. For example, in Figure 4, the distribution of effluent values for BOD_5 for a treatment process is known and displayed in the upper line. This same treatment process is to be used to achieve a maximum effluent BOD of 10.0 mg/L with a reliability of 99.9%, that is, it is not exceeded more than one day approximately every three years. The treatment process to which the data set corresponds produces an effluent of 10.0 mg/L BOD_5 with 90% reliability—the 10 mg/L line from the Y-axis intersects the line fitted to the data points at the 90% line from the X-axis. To find the design mean for the same treatment process dimensioned to achieve 99.9% reliability, place a point on the graph corresponding to 10 mg/L and 99.9% reliability. The treatment process is assumed to have the same variability of performance, so a straight line is drawn through that point, parallel to the straight line fitted to the data set. The new design mean is where the new line intersects the 50% value, or about 2.1 mg/L.

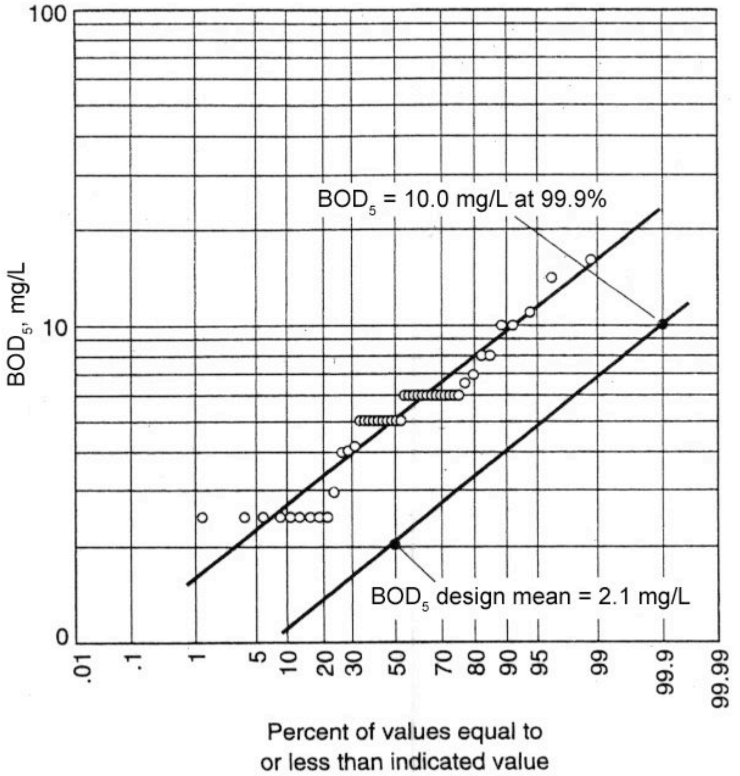

Figure 4. Probability Distributions for BOD5 in Effluent from a Treatment Process Are Used To Calculate the Design Mean for the Same Treatment Process Dimensioned To Achieve 10.0 mg/L BOD_5 At 99.9% Reliability. Adapted from (Metcalf & Eddy 2003).

The examples thus far have been for parameters which vary continuously. For binary (pass-fail) parameters, the graphical method can be used if the Y-axis is time to failure. For example, if the Y-axis is time to failure of a SAS and it was determined that most or all failed SASs were not reported to the regulatory authority, then the graph could be used to set a minimum inspection interval. A standard of reliability could be set, e.g., no more than 10% of all systems will be failed at any given time. From the line fitted to the data points, read over to the time (Y) axis to determine how long after installation 10% are likely to be failed, and set an inspection interval shorter than that time period.

COSTING TOOLS

The following sections contain a summary of parts of the costing section of the handbook. Principles important for conducting costing analyses that are rarely consistently observed are discussed. Two of the tools that are focused on in the handbook are presented in some detail, while the other tools are briefly summarized.

Things to take into account when costing

There are three important principles that affect the way costing tools are applied and the usefulness of their application:

- The time value of money;
- Which costs are included/excluded; and
- Uncertainty and risk

These principles are explained very briefly.

Time value of money

The real value of money changes over time. If you are interested in comparing alternative wastewater solutions over long time periods, then this change in value will likely be significant. In fact, even over relatively short time periods (as little as three years), taking into account the time value of money can influence the costing analysis and associated decision making.

So how does the value of money change over time? A simple example, $1000 received today would be worth $1050 next year if you invested it in the bank at an interest rate of 5%. Similarly, if you will receive $1000 next year, this money is only worth $952.38 now if banks are offering 5% interest.

We use a rate called the discount rate to account for this change over time. Many different ways of estimating an appropriate discount rate exist. A good starting point for wastewater infrastructure is 2% for a 10-year period, and 3.5% for a 30-year period.[1] However, the context and timing are important and sometimes values as high as 5 or 6% over 20 years are used.

The following formula translates a single cost that will take place in the future to its equivalent cost today, which we call its present value (PV) or its present worth.

$$PV = C_n(1+X)^{-n}$$

Where PV is the present value of a future cash flow
X is the discount rate
n is the specific year that the cost occurs
C_n is the nominal cash flow in the nth year

Annualized cost is another way of accounting for the time value of money.

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[1] Current real discount rates for use in the US can be found at http://www.whitehouse.gov/omb/circulars/a094/a94_appx-c.html

Which costs are considered

This section discusses how to make decisions about what costs you include or exclude in your analysis. We will discuss three important aspects that influence which costs are considered.

Life cycle approach

Using a "life-cycle approach" means that you consider costs incurred throughout all the stages of the life cycle of an onsite system. If you are only interested in certain stages of a system's life cycle, you may specify which stages you are including or excluding in your analysis. If, for instance, a manufacturer of onsite systems is able to give homeowners information about the life-cycle cost of different systems they produce, then the homeowner will be able to see clearly the differences in operation and maintenance costs that they will be confronted with in the future if they invest in a particular system. A more reliable system might cost more up front, but may cost less over time if the whole life cycle is taken into account.

Cost perspectives

Making clear which the "cost perspective" is used in a costing analysis is very important. Analyses often only take into account the costs that directly affect the party conducting the costing analysis. However, it may well be the case that other parties will incur monetary or non-monetary costs that will be ignored by this analysis.

Sometimes it is appropriate to include a single cost perspective, while other times it is important to consider multiple cost perspectives. This concept is important with respect to the reliability of onsite systems, because improving reliability often depends upon decisions being made that are based on multiple cost perspectives.

For services that we believe are a fundamental need, such as water supply or wastewater treatment services, it is useful to consider the "least cost to society". That is, we accept that this service is necessary for all people, and we analyze how we can provide this service to all people at the lowest possible overall cost. This sort of analysis is called an economic analysis.

Calculating the "least cost to society" means including costs of damage to the environment and other "externalities" (such as risks or social costs) that are commonly excluded if costing is only done from one perspective. Externalities can be given monetary values through a variety of valuation techniques, or sometimes are considered separately from the costing analysis.

If the "least cost to society" is investigated, it is much more likely that reliability will be given priority, or at least be considered, in decision making. More reliable systems (or more easily maintained systems), though potentially more expensive at the outset, will incur lower future costs to their owners and less risk of damage to public health or ecological systems through exposure to treated wastewater.

Uncertainty and risk

Uncertainty is inherent in all cost analyses, though it is often left implicit. Unforeseen variations in future costs result in significant changes to the key inputs of financial and economic analyses. Experience and good judgment can inform the level of uncertainty, and various quantitative methods are also available to support the rigor of decisions.

Some guiding principles are useful when presenting uncertainty and risk in economic analyses.[2] The most important point is that you provide descriptions of all known key assumptions, biases, and omissions. If possible, you should also perform a sensitivity analysis on your key assumptions.

Risk is important in cost analyses related to reliability in a few different ways. There is a financial risk for a person or organization that makes an investment. Other types of risks, such as environmental, socio-economic, or public health risks, are potential results of decentralized systems that operate unreliably.

Life cycle costing (LCC)/cost-effectiveness analysis

How is this tool useful and applicable to influencing the reliability of decentralized wastewater systems? Why is it worth using life-cycle costing and what questions can it help us answer? Here are some examples:

- Which one of several possible wastewater solutions should we choose? Should we choose a less complex system that will be easier to maintain? Is it worth building in redundancy and investing more in capital costs, in the hope of reducing on-going maintenance and repair costs?
- What operation, inspection and maintenance regimes will cost the least but give the greatest benefit in terms of reliability and reduced risk of a set of systems?
- What is the most cost-effective approach to take towards system or component repair, replacement, rehabilitation or life extension, and disposal?
- How should we allocate our funds towards different competing priorities?
- What are the most significant costs associated with operating a particular type of system?
- Would a demand management program be a cost-effective way to reduce hydraulic load on a system and therefore improve its reliability (or at least reduce its on-going maintenance and pump-out costs)?

Though in many cases the LCC tools exist, the necessary data to input to the analysis in order to answer these sorts of questions will likely not be immediately available. This hurdle may be overcome by making assumptions based on past experience, or by collecting the necessary data once the scope of the desired analysis has been decided.

What is life-cycle costing? Life cycle costing assesses the total cost of both acquisition and ownership of a product or system. Often in decision-making for small wastewater systems, only capital costs of a technology or project are considered. This can lead to the selection of systems with low capital and high operating costs. High operating costs can be associated with costly repetitive maintenance, risk of failure through poor design; or inefficient resource use (such as high energy or water consumption).

Calculating the life cycle cost (LCC), that is, the cumulative cost of a product or system over its life cycle, allows proactive decisions and wise investment. The life cycle costing tool is a way to predict the most cost-effective solution over the long-term.

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[2] Cf. US EPA (2000) Guidelines for Economic Analyses for additional information about analyzing and presenting uncertainty (p. 27-30).

It is therefore usually used as a form of “cost-effectiveness analysis” that helps tell you the best way to minimize the cost of achieving specific goals.

The life cycle phases commonly included in analyses are shown in Figure 5.

How do you do life cycle costing? The process of life cycle costing involves several different steps, each of which is indispensable. For instance, jumping straight into the development of a life cycle costing model, without first thinking through the aims and objectives of your analysis, will lead to wasted work and unclear outcomes. Even if you use a commercially available LCC tool (such as http://www.relexsoftware.com/products/lcc.asp), you still need to work through the steps of the analysis, which are described below.

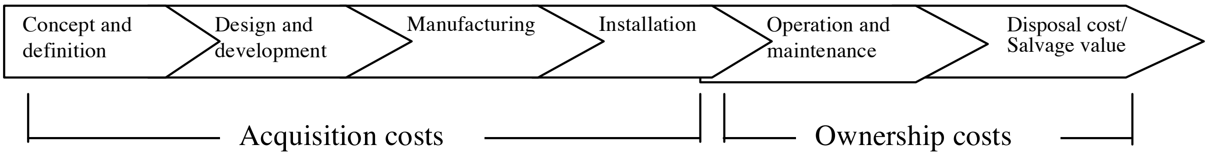

Figure 5. Life Cycle Phases Commonly Included in Analyses.

Step 1. Planning

Be clear about the question you want to answer. Life cycle costing is a versatile tool that can be used in many different ways. Other parts of the planning process include defining the scope of the analysis (are you focusing on a component of the onsite system, or the system as a whole?), defining the operating and maintenance support scenario, identifying constraints and limitations which will limit the acceptable options to be evaluated, identifying alternative course(s) of action to be compared with the base case, considering the resources and data required to conduct the analysis, and finally, defining a reporting/communication plan for the results of the analysis in support of decision-making processes.

Step 2. Creating a life cycle model

A life cycle model is an accounting structure that contains an aggregation of all the possible costs associated with a system over its lifetime (or of the particular phases that you have chosen to analyze). To identify and articulate all these different costs systematically, you first need to create what is known as a Cost Breakdown Structure (CBS).

Step 3. Conducting analysis using the LCC model

Here, the net present value (NPV) of different options/scenarios is calculated. A certain time-span must be chosen for the analysis so that comparisons between alternatives can be made on an equivalent basis. The net present value (or net present worth) is calculated as follows, discounting each future cost back to its worth today, and adding together all of these amounts:

$$NPV = \sum_{n=0}^{T} C_n \left(1 + X\right)^{-n}$$

Where	NPV	is the net present value of future cash flows
	C_n	is the nominal cash flow in nth year
	n	is the specific year in the life cycle costing period
	X	is the discount rate
	T	is the length of time period under consideration

NPV can be easily calculated using a Microsoft Excel™ spreadsheet. Sensitivity calculations may also be done on the NPV to analyze the impact of different assumptions, discount rates, and cost element uncertainties on LCC model results. Results should be documented, making clear the limitations and uncertainties associated with the results.

Risk-cost tool

The risk-cost tool allows you to arrange a set of assets in a hierarchy of highest risk-cost down to lowest risk-cost, and to focus your attention on those assets with the highest risk-cost over a given time period. Based on the risk-costs in this hierarchy, you can make an assessment of the cut-off point at which it is worth intervening with inspection, preventive maintenance, or replacement.

The risk-cost of an event is a multiplication of the dollar consequences of an event and the probability of that event occurring in a given period of time. To use this tool, the dollar value of the consequences of a failure and the probability of that failure both need to be determined or estimated. You can use varying levels of determination along a spectrum from a broad-brush estimation to detailed modeling based on multiple parameters to determine the most accurate values possible.

The probability of a failure occurring over a given time period may be estimated using reliability tools such as the failure curve. The cost of consequence involves estimating both monetary costs such as the cost to repair, and any environmental or social costs that are incurred by the failure. In the centralized field, leaders in the field of asset management are starting to find ways to value and incorporate these sorts of non-monetary costs. In the decentralized field, it will be necessary to develop appropriate ways to include such costs. Inconvenience to homeowners, risk of public health of homeowners, and potential for ecological impact are examples of the sorts of non-monetary costs that will need to be considered to use this tool.

In the centralized wastewater sector, there is now a move away from investing great effort in very detailed reliability and cost modeling to come up with accurate probabilities and costs of failures. This came about due to experiences that showed that the degree of uncertainty inherent in the many of the parameters used in the models, as well as the influence of unpredictable external factors, often undermined the accuracy of predicted results. A less rigorous approach involves categorizing components of onsite systems or sets of complete onsite systems in a table (Table 3).

Table 3. An example of categorizing onsite system assets (components of onsite systems or sets of onsite systems) according to the probability and consequences of their failure.

Probability / Consequence of failure ($)	1 (low)	2	3	4	5 (high)
5 (high)				Asset group E	Asset group D
4		Asset group F			
3	Asset group A				
2		Asset group B		Asset group H	
1 (low)	Asset group C	Asset group G			

Using this matrix, even if detailed reliability data or costing information is not available to give you an accurate estimate of the probability of failure, it will still be possible to see which assets which are the most strategic to focus on. In Table 3, it would make sense to initially focus attention on asset groups E and D.

BRIEF DESCRIPTIONS OF OTHER RELIABILITY AND COSTING TOOLS

In addition to the costing and reliability tools presented in detail in this paper and explored during this project, we plan to include the following tools at some level in the handbook.

Reliability Tools

Probability assessments, such as mean time before failure (MTBF), mean time to repair, and operating availability. These can easily be calculated once data from actuarial studies have been gathered. When the shape of the failure curve is known, then it is possible to know how to apply each of these assessments to management decisions.

Cohort analysis is a species of actuarial study. A cohort is defined as a set of systems sharing common characteristics. In *simple cohort analysis*, the two characteristics used are the regulations in effect at the time a system is constructed and the soil type the system is built on. More complex cohort analysis could include such things as system designer, installer, system type, etc.

Failure modes and effects analysis is a procedure that identifies potential component failures and assesses their effect on the system. It allows prioritization of failure modes according to their frequency and criticality so more effort can be spent in fixing high-priority failure modes.

Critical component analysis concentrates actuarial studies on the components identified as being most critical to system performance.

Field sampling of performance of a subset of wastewater treatment systems can provide data on what factors correlate with poor performance. Hoover (2003) has devised a step-by-step procedure to generate statistically valid results.

Systematic troubleshooting of systems diagnosed with problems, combined with systematic inspections, is a basis for accurately recording the condition of systems. When the cause of a problem is accurately identified and other potential problems are identified before they create problems, then more finely granular data for actuarial studies are produced.

Geographic information system (GIS) tools can be used to complement cohort analyses. They produce visual representations of clusters of failures, and these maps can suggest hypotheses to explore statistically using cohort analysis: e.g., "Systems built on soils with groundwater less than three feet from the surface are more likely to fail than other systems."

Costing Tools

Activity based costing (ABC) will be useful to anyone, particularly an RME, who wishes to do life-cycle costing. This method requires costs to be directly linked with the activity that generates the cost. This is in contrast with usual methods of accounting in which costs are often lumped by department or other grouping. This method is a powerful tool that has the potential to show accurate and complete costs for a particular product or area of endeavor.

The more activities that need to be carried out, the higher the cost is likely to be. This tool involves determining the resources (time, labor, etc.) needed to carry out a particular activity in support of a particular goal (usually a product or a service). Some of the changes that using this tool might provoke are examining the real cost of using scarce resources for capital expenditure and determining what labor time was spent on an activity.

Activity based costing is very similar to the steps required by life cycle costing when the cost breakdown structure is developed.

Economic life replacement analysis relies heavily on detailed reliability analysis, and then adds in a cost component to make decisions about the most cost-effective way to maintain a set of onsite systems. It is used in the centralized field for replacement/rehabilitation management of pipes, and it may be possible to use it for various components or the whole onsite system. Reliability tools are needed to inform this analysis. The cost modeling is applied simply to weigh the costs of continuing to repair an older component or system versus replacing the component in question. This approach is often used when probability of failure is high, but the consequence is low.

The "economic life" of a component is reached when the cost of replacement is less than the cost of continuing to repair it, all costs included. A model is created to determine the point at which it costs less to replace the component rather than leave or repair the component. The model is based on factors such as:

- Repair costs
- Historical frequency of failure
- Replacement cost
- Discount rate
- Residual value of the replacement component in X years (end of analysis period)

- Likely rate of increase of failure in the future if replacement does not occur
- Social cost to the community (e.g. discontinuity of service)

Analysis of trends in maintenance costs: If a detailed cost inventory is kept then it will be possible to look for trends, so that you can be proactive about maintenance and make informed decisions as a part of the yearly engineering review. This might involve costing the dominant failure mode(s) and determining whether it will be less expensive to deal systematically with this mode of failure than to allow it to happen and deal with the consequences. For example, a practitioner or RME could look at the cost of pumps that have been purchased and failed prematurely versus the cost of a higher quality pump with longer life (maybe warranty periods are also longer). They could also look at how many pumps/parts to have on-hand for an emergency versus buying materials on an “as-needed” basis.

Cost benefit analysis (CBA) will be useful to regulators and potentially to large RMEs. Cost benefit analysis helps you evaluate the positive effects of an action and the associated costs of that action. The positive effects are called benefits and the economic costs are deemed opportunities foregone. The main objective of CBA is to compare social costs and benefits.

Various economic methodologies estimate the value of anticipated benefits and costs. This analysis always includes comparisons of costs and benefits to the whole of society. “Whole of society” implies all stakeholders including the public or community that can be potentially impacted by the decision.

When deciding which benefits to include in your analysis, you need to consider “avoided costs”. “Avoided costs”, or “avoidable costs”, are costs that are ‘avoided’ relative to a base case or business-as-usual course of action, but which are avoided by certain choices about how things are done in the future. For options that improve reliability of decentralized systems, avoided costs may include: avoided environmental damage, avoided costs of other damage or risk posed by failure, saved water or saved energy, and avoided maintenance costs (e.g. if the option includes water efficiency measures that reduce hydraulic load on the system).

Integrated resource planning (IRP) framework is a tool useful to regulators. Integrated resource planning (IRP) is an open, participatory, strategic planning process, emphasizing least-cost analysis of options for meeting utility supply service needs. It was developed for the electricity industry in the United States in the 1980s. Its aim was to compare energy demand management programs with increased generation as sources of supply. The basic premise of IRP is that the utility should treat bulk supply and conserved supply as equivalent. Demand side management is central to IRP, with demand management being any program that modifies (decreases) the level and/or timing of demand for water or energy. Demand management programs are designed to promote conservation through either changes in consumer behavior or changes to the stock of water or energy using fixtures, such as showerheads, toilets or light bulbs.

Demand management programs have the potential to reduce water use and thereby reduce hydraulic load on onsite systems, which is likely to improve their reliability and reduce required maintenance.

Cost perspective tests are also tools useful to regulators. Cost perspective tests are a way of looking specifically at a particular party’s cost perspective to determine whether a program or option/scenario) would be beneficial to them or not. These were initially developed for economic analysis of demand-side programs and projects and include five tests: Participant Test, Ratepayer Impact Measure Test, Total Resource Cost Test (and variant Total Societal Cost Test), and Program Administrator Cost Test (utility perspective).

If a regulator wished to examine and compare some different programs to improve reliability of onsite systems, the Participant Test might be useful to determine the quantifiable benefits or costs to a homeowner based on reduction of any of their maintenance costs, tax credits received, or incentives paid, balanced by any out of pocket expenses the program caused or other costs such as the value of their time if some form of participation is needed. Equally, the Ratepayer Impact Measure Test would be useful to examine effects on pricing costs to homeowners of a program that changes the revenue and costs of an RME. The Total Resource Cost Test (and its variant, the Total Societal Cost Test) would be useful to measure the net costs of a particular program. Here, the benefits are usually avoided costs (see description above). Transfers of cash between different parties (such as the homeowner and the RME) are excluded from this analysis.

CONCLUSIONS

As the decentralized wastewater industry grows and is acknowledged as a viable, long-term solution to waste treatment and disposal, greater focus on improving decision making related to the reliability of the technology and the cost of installation and maintenance of these systems will become necessary. The current level and interest of regulators and the industry in seeing the creation of more RMEs and the realization that federal regulations such as GASB 34 will need to be complied with, are factors which will provide additional pressure to implement such approaches.

Fortunately, there are many examples of thinking models and tools for specific applications that, while developed for other industries are directly applicable to decentralized wastewater decision making. The framework developed for this project is a good example of adapting the traditional planning loop model to the industry's needs.

Of importance to the framework is the need to consider carefully so many important issues early in the process. Both the issues which influence the decision making, (environmental and organizational contexts and regulations and policy matters), as well as understanding the current situation and the goals for the solution represent important thinking that will ultimately improve decision making if the time is made to consider these issues. In this industry, communication strategies and the need for a data information system are especially acute due to the nature of our work – a "decentralized" industry. Without proper commitment to these elements, projects will be at risk of being ill informed or un-supported.

With a sound process in place, tools and models are essential to allowing for new types of thinking to occur relating to improving reliability or improving financial decision making. Tools such as failure curves, coefficient of reliability, life cycle costing and the risk-cost model are examples of tools that can be used today to positive effect in many cases.

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