A PARAMETRIC SIMULATION MODEL FOR EVALUATING COST EFFECTIVENESS OF REMOTE MONITORING FOR RISK REDUCTION IN RURAL WATER SUPPLY SYSTEMS AND APPLICATION TO THE TAZEWELL COUNTY, VIRGINIA SYSTEM

by
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Abstract

A simulation model analyzes cost effectiveness of remote facility monitoring for risk reduction in rural water supply systems by performing a break-even analysis that compares operating costs with manual and remote monitoring.

Water system operating cost includes the value of water loss (i.e., realized risk) resulting from operating excursions which are inversely related to mechanical reliability. Reliability is controlled by facility monitoring that identifies excursions enabling operators to implement mitigating measures.

Cost effectiveness refers to the cost relationship among operating alternatives that reveals changed economic conditions at different operating rates inherent in the inverse relationship between fixed and variable costs. Break-even analysis describes cost effectiveness by identifying the operating rate above which the more capital intensive alternative will result in lower operating cost.

Evidence indicates that increased monitoring frequency associated with remote monitoring can reduce water system operating cost by improving reliability, but whether remote monitoring is cost effective depends upon system-specific factors. The lack of a documented tool for evaluating this type of cost effectiveness led to the project objective of developing a model that performs break-even analysis by simulating water system operating costs as functions of system size (delivery rate).

When the spreadsheet-based static deterministic parametric simulation model is run for the Tazewell County, Virginia water system based upon 1998 data, break even is predicted at approximately fifty-five percent of annual capacity (116,338,000 gallons) with operating cost of $1,043,400. Maximum annual operating cost reduction from a $317,600 investment provides payback in nine years.

Acknowledgements

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Part I – Thesis and Project Overview

1.1 Thesis Overview

1.1.1 Research Problem and Objectives

Estimates indicate more than 200,000 small or non-community water supply systems in the United States. (Lynkins and Clark, 1996) These rural systems rely upon assemblages of mechanical components, typically consisting of pumping, treatment and storage devices connected to extensive piping networks, operated to economically treat and deliver water to customers. The operating cost for such a system or the cost of potable water delivered is a function of mechanical reliability, or *delivery efficiency*: the ratio of potable water delivered to potable water produced. In practice, delivery efficiency is typically much less than unity due to water loss resulting from operating excursions such as storage vessel overflow or mechanical component failure.

The monetary value of such water loss constitutes realized fiscal *risk* to a water system that is reflected in its operating cost. With fixed mechanical configuration, delivery efficiency is determined predominantly by the frequency of routine component monitoring that identifies operating excursions thus enabling system operators to implement corrective measures to reduce excursion duration, thereby improving delivery efficiency, or equivalently, reducing realized risk.

A national review of water system operating information indicates that rural water systems may incur more risk than larger systems due to monitoring budget constraints. (NRC, 1997) Currently, the vast majority of these water systems rely upon *manual monitoring*, which is conducted by human observation and movement between monitoring locations and a common decision-making location. *Remote monitoring* can increase monitoring frequency by electronically sensing and transmitting monitoring data, generally in real time. Because the level of water system risk is inversely related to the level of facility monitoring, it is expected that a well designed and implemented remote-monitoring system can be an effective risk-reduction method.

However, in the past, remote monitoring was perceived as prohibitively expensive for small water systems, although recent hardware and software advances may have changed this. (Haught and Panguluri in Cotruvo, Craun and Hearne, 1988) Recently, utility authorities have reported that implementing remote monitoring can greatly enhance small water system operation and maintenance, and that modernizing operating equipment with remote monitoring can reduce operating costs. (Haught, Meekes and Goodrich, 2000) (May, 1997) For example, Entus notes cost savings from operating lift stations with remote monitoring in Plantation, Florida. Although such reports espouse the benefits of remote monitoring, it is essential to understand that improvements to delivery efficiency are not accomplished without cost, and consequently, whether remote monitoring will be cost effective for a particular water system depends upon system-specific factors.

Describing remote monitoring cost effectiveness requires determining water system operating cost as functions of operating rate for manual and remote monitoring. No literature describing formal cost justification methods specific to this type of application were identified during the research phase of this thesis. Similarly, a study sponsored by the American Water Works Association (AWWA) revealed no documentation of formal cost justification procedures for water system automation. The AWWA report further noted that current control system planning practice does not incorporate cost-effectiveness analysis, and concluded that further research is needed in this area. (Schlenger, Riddle, Luck and Winter, 1982)

This paucity of available information and unavailability of such a tool motivated this thesis project (the Project), which was part of a more comprehensive research undertaking by the Virginia Polytechnic Institute and State University (Virginia Tech) Department of Agricultural and Applied and Economics and the Virginia Water Resources Research Center. The goals of this undertaking were to establish a general understanding of risk in rural water systems, and more specifically to evaluate cost and operational implications of remote monitoring for reducing such risk.

These goals led to establishing a Project-specific definition of risk and objective of developing a formal protocol for evaluating cost effectiveness of remote monitoring for rural water systems. Additional research subsequently led to the specific Project objectives of developing a spreadsheet–based parametric simulation model for evaluating remote-monitoring cost effectiveness and applying the model the Tazewell County, Virginia water system.

This thesis is submitted for approval as partial fulfillment for the degree of Master of Science in Agricultural and Applied Economics at Virginia Tech. It primarily documents the results of the effort to develop the simulation model and example application, and includes discussion on background research that provides the conceptual and technological context for the model.

1.1.2 Methods and Results Summary

The Project was executed in two phases: the research phase and the model development and application phase. Accomplishing the research goals and Project objectives required prerequisite research in three subject areas: fiscal aspects of water supply systems including remote-monitoring technology, fundamental concepts relative to establishing a Project-specific definition of risk, and theoretical concepts related to developing a practical cost-effectiveness analysis. Sufficient understanding of these three broad subject areas enabled synthesizing a conceptual model of water system risk reduction followed by mathematically formulating the principal risk/cost relationships followed by developing a spreadsheet-based simulation model.

Upon establishing an understanding of water systems as three interrelated subsystems: the physical subsystem, the operational/personnel subsystem and the fiscal subsystem, the impact on risk associated with replacing manual monitoring with remote monitoring was assessed based upon two sets of information: literature about water system design and operation, including remote monitoring, and historical operating information for the Tazewell County, Virginia water system. (Dowdy, 2002) (TCPSA, 2002) A Project-specific definition that describes risk in terms of the monetary value of water loss enabled formulating the fundamental model concept: improved delivery efficiency can make remote monitoring cost effective at operating rates where the additional fixed cost is outweighed by the reduced variable cost.

This concept of cost effectiveness refers to the cost relationship among operating alternatives that reveals a changing economic condition at different operating rates implied by the inverse relationship between fixed and variable costs. When cost effectiveness is evaluated by break-even analysis, a break-even point indicates the operating rate above which the more capital intensive alternative will be ”cost effective,” i.e., result in lower operating cost. However, it is possible that break even may not occur at operating rates applicable to the system under study, in which case the more capital intensive alternative will never be cost effective.

This concept of break-even analysis was mathematically formulated into a system of equations that describe total water system operating cost with either manual or remote monitoring. These equations were then employed as the basis of a spreadsheet-based model that performs a graphic break-even analysis. The model was applied to the Tazewell County, Virginia water system as the trouble-shooting phase of model development and to evaluate cost effectiveness of remote monitoring for this water system.

The spreadsheet model performs a break-even analysis by simulating water system total operating costs as functions of water system delivery rate, where total operating cost is defined as the sum of fixed and variable costs over an annual operating period. At each operating rate, the remote-monitoring total cost differs from the manual-monitoring total cost in accordance with the increased fixed cost associated with remote monitoring and a decreased unit variable cost represented by a decreased variable cost parameter.

These variable cost parameters are the primary model parameters as they represent the unit variable costs of water system operation with either manual or remote monitoring. The model calculates the remote-monitoring variable cost parameter by applying a set of (secondary) remote-monitoring parameters to adjust the manual-monitoring variable cost parameter to account for improved delivery efficiency attributable to decreased operating excursion duration.

The spreadsheet model consists of one workbook containing six spreadsheets and two break-even charts. The first spreadsheet is dedicated to explanatory notes and instructions. The other spreadsheets either require user input/interface, make calculations or both. Upon receiving all required input the model automatically performs the necessary calculations and generates the break-even charts.

The model requires input that is grouped into four categories, flow data, cost data, user-defined monitoring parameters and present-worth parameters. Flow data consists of monthly quantities of potable water produced and delivered for the water system, generally obtainable form system operating records. Cost data are grouped into three subcategories. Annual fixed costs for the existing water system (manual monitoring) are selected based upon entries in accounting documents such as annual financial reports. Variable costs for the existing water system are generally available as entries in revenue statements. Additional fixed costs associated with implementing remote monitoring are based upon categorized estimates for the specified remote-monitoring configuration.

There are three user-defined monitoring parameters. The remote-monitoring extent factor defines the extent to which remote monitoring will be implemented based upon water system size, mechanical components designated for monitoring and other characteristics. The manual- and remote-monitoring frequencies are factors that specify a weighted average monitoring frequency in either mode.

Present-worth parameters are used in the model to convert cost inputs to present-worth values for existing water system fixed and variable costs. The user must specify applicable interest rates and the number of years from the present in the equivalent-worth calculations. Interest rates may be selected based upon actual bond rates or common indices such as the consumer price indices published by U.S. Bureau of Labor Statistics. For the example application the interest rate associated with fixed costs was calculated as the dollar-weighted average of outstanding bond interest rates, and the interest rate associated with variable costs was calculated based upon the consumer price index for all urban consumers and industrial commodities less fuels.

Although the model is particularly sensitive to certain user-input parameters, when these are adequately understood and estimated, it can serve as a useful decision-support tool. When the model is so used in conjunction with other cost-justification methods such as payback period, it provides valuable information upon which to base investment decisions.

Applying the model to the Tazewell County, Virginia water system based upon 1998 production and financial data predicts break even at approximately fifty-five percent of annual capacity (116,338,000 gallons delivered), which corresponds to an approximate total annual operating cost of $1,043,400. In this simulation, replacing manual monitoring with remote monitoring increased annual fixed costs from approximately $644,000 to $690,000, and the variable cost parameter decreased from $3.43/1000 gallon to $3.04/1000 gallon, accounting for a total operating cost reduction of $37,200 at the simulated operating limit. This annual operating cost reduction gives a payback period of nine (9) years from a $317,600 investment in remote monitoring.

In addition to describing remote monitoring cost effectiveness for the Tazewell County water system, the example application revealed nuances of input data sources and the user-estimated input parameters about which the user must be cognizant when applying the model.

1.1.3 Definitions

The following definitions used throughout this thesis in some cases differ from common definitions.

- benefit: (1) positive consequence of system operation. (2) monetary value associated with positive consequence.
- break-even analysis: type of cost-effectiveness analysis for evaluating alternative systems that describes the changing economy of alternatives at different operating conditions as a relationship between fixed and variable operating costs and includes the concept of a break-even point.

- break-even point: system operating condition (e.g., operating rate) corresponding to the intersection of total cost functions of alternatives evaluated by a break-even analysis. The break-even point indicates the operating condition above which the more capital intensive alternative will be "cost effective," i.e., result in lower total operating cost.
- cost: (1) monetary value of a production input (see also *fixed cost* and *variable cost*). (2) negative consequence of system operation or monetary value associated with negative consequence.
- cost effectiveness: (1) relationship between system operating costs and benefits described as the result of cost-effectiveness analysis. (2) with reference to break-even analysis, the attribute of the more capital intensive alternative above the break-even point.
- cost-effectiveness analysis: (1) decision-making method for analyzing economic values of systems with similar objectives in which benefits can be measured in non-monetary terms. (2) generally, any decision-making method that compares alternative system benefits and costs, such as break-even analysis.
- decision-support tool: procedure or information system used to support a decision-making process.
- delivery efficiency: ratio: volume potable water produced/volume potable water delivered.
- fixed cost: cost that does not vary during a production period.
- loss (of water): (1) the amount or fraction of potable water lost prior to delivery. (2) monetary value associated with potable water lost prior to delivery.
- manual monitoring: water system operating data acquisition by human observation and movement between monitoring locations.
- MIS: Management Information System; computer-based system for acquisition, manipulation and display of organization-, task- or financial-based data.
- monitoring frequency: the number of monitoring events per unit time at a monitoring location.
- monitoring event: acquisition of water system operating data at a monitoring location and transmittal to a decision-making location.
- operating excursion: water loss causing condition such as storage vessel overflow or mechanical component failure.
- operating rate: operating system variable describing quantity of product generated per unit time, e.g., volume of potable water produced per year.
- operational risk: see *risk*.
- parameter: model constant.

- parametric cost estimating: cost estimating method based upon mathematical expression relating cost as a dependent variable to one or more independent cost-estimating variables or parameters, where independent variables are typically related to system size or other operating characteristic.
- physical plant: set of indivisible physical production inputs existing at a specified time or production period, generally consisting of durable goods such as land, buildings and equipment.
- planning horizon: the time to which all decision-making variables have meaning or the time beyond which the values of decision-making variables are ignored.
- realized risk: (1) actual water loss resulting from uncorrected operating excursions. (2) monetary value or cost associated with water loss. (see also *risk*, below)
- remote monitoring (remote telemetric monitoring): water system facility operating data acquisition by electronic sensing at monitoring locations and telemetric transmission to a decision-making location.
- response time: the time between detection of an operating excursion ascertained by a monitoring event and initiation of corrective action.
- risk: (1) potential for water loss resulting from uncorrected operating excursions. (2) monetary value or cost associated with water loss.
- rural water supply systems: water systems serving rural populations, usually dispersed throughout a geographic area and consisting of one or more individual water systems.
- SCADA: Supervisory Control and Data Acquisition. See *remote monitoring*.
- sensitivity analysis: determination of how a model solution changes in response to parameter value changes.
- simulation: process by which understanding of the behavior of a physical system is obtained by observing the behavior of a model representing the system.
- system delivery efficiency: See *delivery efficiency*.
- system operating rate: See *operating rate*.
- telemetric monitoring: See *remote monitoring*.
- telemetry: collection and electronic transmission of system operating data, such as by telephone, radio or satellite link (usually in real time).
- variable cost: cost that varies as a function of output during a production period.
- water loss: See *loss*.

1.1.4 Thesis Format

In addition to the front matter and back matter, this thesis is organized into four parts that collectively contain thirteen sections, each of which is further divided into various subsections, as shown in the table of contents. The two sections comprising Part I give overviews of the thesis and research project, and includes a list of important definitions used throughout the thesis. One section of Part II discusses fundamental concepts that provide the basis of the parametric cost simulation model, and one section describes the spreadsheet-based model from conceptualization and mathematical formulation through execution. Part III consists of four sections that describe application of the model to the Tazewell County, Virginia water supply system. Certain sections of Part III serve in conjunction with Part II to explain details of the model by example, particularly how to modify raw data and select input. Part III also presents a numerical model sensitivity analysis based upon the example application. Part IV summarizes and presents brief conclusions and recommendations in four sections corresponding to the four principal topics addressed by the research undertaking: remote monitoring technology, the simulation model, remote monitoring for the Tazewell County water system and remote monitoring for rural water systems in general.

Reduced or summarized data for the example application are presented in the body of the thesis, and data sources are included in the references. All figures, tables and spreadsheets are labeled collectively as exhibits, and are numbered sequentially within each of the four parts.

1.2 Background Information

1.2.1 Three Subsystems Comprise Water Supply Systems

Water supply systems can be understood as consisting of three subsystems, the physical subsystem, the operational/personnel subsystem and the fiscal subsystem, operating interdependently to deliver potable water to customers.

The physical subsystem consists of all physical features that comprise water systems or affect their operation. These interrelated features can be organized into five categories: geographic features, mechanical components, general infrastructure, existing communications infrastructure and remote-monitoring infrastructure.

Geographic features such as topography, surface type and other natural and anthropogenic conditions determine the physical setting of the mechanical and infrastructure components. Geographic features affect risk because monitoring response time and operating excursion duration are functions of geography, particularly with manual monitoring.

Mechanical components consisting of pumping and treatment units, storage tanks and distribution piping are the fundamental functional parts of the water system. These components physically generate and deliver the system product, potable water, to customers. Water system delivery efficiency is a function of mechanical component reliability, or conversely, operating excursion duration. Mechanical components are designed to extract, treat and transmit water from its source across the geography of the service area to customers, and are therefore designed based upon three primary considerations - water quality, hydraulics and economy. (Clark, Visseman and Hammer, 1977)

The purpose of treatment is generally to provide potable water, which is chemically and bacteriologically safe for human consumption and suitable for certain industrial uses. (Clark, et. al., 1977) Treatment systems are designed and operated to treat source-specific water so potable water will meet primary and secondary drinking water standards of the Clean Water Act Amendments. These standards include water quality parameters for microbial contaminants, turbidity, pH, residual free chlorine, total organic carbon, hardness and total dissolved solids. (Pollack, Chen, Haught and Goodrich, 1999) Treatment methods depend upon the water source and the desired potable water quality, but may typically include retention or equalization, screening, pre-sedimentation, aeration or other oxidation processes, precipitation softening and filtration. Water supplies from rivers normally require the most extensive treatment and supplies from wells the least treatment. (Clark, et. al., 1977)

Water-distribution systems are normally designed to meet water quality and system pressure requirements for a combination of domestic, commercial, industrial and fire-fighting uses. Hydraulic considerations include transmitting potable water from the treatment plant to storage components, thence to customers according to limitations imposed by geographic features. Transmission system design involves hydraulic and structural adequacy, hydraulic considerations being intimately related to water system economics because hydraulic head has real economic value, and there is therefore a definite relationship between transmission system design and operating cost. A basic system requirement is the provision of adequate pressures at specific flow rates, and although pressures must be adequate to meet customer demand and fire-fighting needs, they must not be excessive for two principle reasons. First, because of the relationship between pressure head and cost, and second, because water loss through leakage increases with increased pressures. (Clark, et. al., 1977)

Distribution systems may be classified as grid systems, branching systems or combination systems, dictated primarily by topography and street patterns. In hilly or mountainous regions it is common practice to divide the distribution system into more than one service zone. Conduit types and sizes are selected based upon the most economical design that conforms to the necessary operating procedures and hydraulic gradients. Storage units are located and sized to provide adequate supply in times of emergency or other outage, and in accordance with the distribution network to optimize hydraulic head. (Clark, et. al., 1977)

General infrastructure such as roads and electric lines, can be utilized for routine component monitoring and operating data transmission with either manual or remote monitoring, although the types of infrastructure utilized and their relative import will be different for either monitoring mode.

Existing communication infrastructure such as telephone and radio systems, can be utilized for operating data transmission with either manual or remote monitoring, although the types of infrastructure utilized and their relative import will be different for either mode.

Remote-monitoring communication infrastructure such as RF systems that would be established specifically for remote-monitoring data transmission are applicable only to remote monitoring.

<u>The operational/personnel subsystem</u> consists of all personnel and corresponding operational tasks associated with water system operation. This subsystem includes the operational organization and procedures that govern routine activities and non-routine activities in response to operating excursions.

Operational organization can be described as the correspondence between system personnel and operating tasks or task effort requirements. This correspondence can be illustrated by a matrix that indicates personnel categories and corresponding tasks such that all task-related costs are represented. Some tasks can be further segregated into routine and non-routine tasks, where non-routine tasks are predominantly those necessary to respond to operating excursions.

The fiscal subsystem consists of the relationships among all money receipts and disbursements (or benefits and costs). Receipts may include customer charges and government funding. Disbursements include expenditures which may be categorized into fixed costs or variable costs, the sum of which is the total operating cost. Fixed costs include those associated with inputs that do not vary during the production period, whereas variable costs include those for inputs that vary with the level of production.

1.2.2 Remote Monitoring Technology and Application

Telemetry, an acronym from telephone and meter is defined as the electronic sensing of information at a remote site and the subsequent transmission of that information to a centralized or convenient location. (Haught and Panguluri in Cotruvo, et. al., 1999) SCADA is an acronym for supervisory control and data acquisition. The terms telemetric monitoring, SCADA and remote monitoring are generally considered synonymous in the context of the Project.

For simplicity, remote monitoring systems can be categorized into three classes based upon level of automation. Supervisory control indicates operator directed system control, usually from a centralized control location. Automatic control involves instrumentation and control equipment to automatically adjust system conditions based upon relatively simple operating rules. Advanced control implies the use of sophisticated optimization algorithms, process models or artificial intelligence. (Schlenger, et. al., 1996)

Remote monitoring systems can provide facility operators a valuable link to water system physical components from production through delivery locations. By scanning RTUs (remote telemetry units) every few minutes, remote monitoring systems can provide essentially real-time information on system status. Because remote monitoring systems can be expensive to install, appropriate technology selection is important. Advantages reported by users of remote monitoring systems include improved operating efficiency and customer service through continuous monitoring of system conditions which provides information for planning and cost savings. (Mastran, 1999)

The basis of remote monitoring software and hardware for water systems is earlier applications in other industries including chemical and petroleum products manufacturing. Recent developments include remote monitoring systems for HVAC control and home security. (Haught and Panguluri in Cotruvo, et. al., 1999) Modern state-of-the-art remote monitoring systems have numerous features such as distributed architecture, distributed databases, graphic user interfaces and intelligent RTUs. (Trung, 1995) The petroleum industry is a mature user of remote monitoring having progressed from basic monitoring and control to real-time process optimization. (Anon, 1999) For example, Amoco Canada’s real-time pipeline model application system interfaces with the company’s SCADA system to enable real-time modeling for batch tracking, composition tracking, leak detection and other functions in the company's Cochin pipeline. (Wray and O'Leary, 1996)

Up-to-date remote monitoring systems usually feature more than one state-of-the-art microprocessor connected by a local-area or wide-area network made possible by advances in computer communication technology featuring standard protocols. Such system architecture provides many benefits including reduced system response time, increased system reliability and simplified system expandability. Modern man-machine interface devices are high resolution full graphic visual display units that may be fitted with mice, trackballs, joysticks and keyboards. With these devices operating in an X-windows environment operators can quickly move between displays and zoom into critical information, modify displays on-line and create special effects to enhance displays, view multiple outputs on a single display, and access data residing in different databases or that are geographically dispersed. Intelligent RTUs can communicate over a wide range of communication media, and can execute many levels of data processing and control. They may include built-in mathematical functions and algorithms that filter data or calculate derived values. The low cost of data storage devices enables SCADA systems to hold massive amounts of data and to exchange data with management information systems (MIS) and geographic information systems (GIS). (Trung, 1995)

Common software on modern SCADA systems can include those that perform automatic startup/shutdown, emergency shutdown, leak detection, real-time performance and diagnostic modeling, meter proving and optimal scheduling. In the petroleum industry leak detection of product systems is of paramount import. Tank leaks are generally detected by monitoring tank volume, whereas pipe leaks may be detected in several ways, such as real-time modeling based upon pressure, temperature and flowrate profiles. (Trung, 1995)

Water system remote monitoring is generally selected to perform one or more of several functions that may include monitoring or monitoring and remote control from a centralized location. It is also possible to select monitoring systems to diagnose various problems remotely and satisfy regulatory record keeping and reporting requirements. Remote monitoring systems for water systems can be categorized as consisting of four groups of components, hardware, telemetry software, communication media and instrumentation. (Haught and Panguluri in Cotruvo, et. al., 1999)

The two primary hardware components are the main computer and the RTU. The main computer may be configured around various operating systems, but is commonly a personal computer operating in a

Windows environment with graphic user interface. The main computer must include application hardware and software to support the selected RTUs. Each RTU consists of a DAQ (data acquisition board), communication equipment (modem, radio, etc.) and an onboard processor. Typically, DAQs plug directly into the computer bus and are cabled into the system PLCs (programmable logic controllers). DAQ driver software manages operation of hardware and low-level system resources. Driver software directly programs registers for DAQ hardware, which manages operation of and integration with computer resources such as processor interrupts and direct memory. The DAQ board communicates with the main computer via serial link using the selected communication device. The RTUs generally include an onboard microprocessor of limited functionality to control the DAQ board via the system bus. (Haught and Panguluri in Cotruvo, et. al., 1999)

Telemetry software is in a state of rapid development, with major improvements occurring at least annually. Commercially available software packages are designed to interface with more popular computer-operating applications, and they use open standards to enable them to be programmed to communicate with a variety of electronic hardware. They generally include the ability to import/export graphics, spreadsheets, databases and text. (Haught and Panguluri in Cotruvo, et. al., 1999)

The communication medium used in a remote monitoring system depends upon geographic location, availability, cost and other site-specific factors. Options are land-based telephone lines (POTS), cellular telephony, radio frequency links and satellite links. Cellular telephones are generally only useful when they are within range of the cellular network because they transmit data via an RF link to a cellular base station, which then connects to a POTS to transmit to the final destination. In most rural water system applications RF link is the application of choice based upon universal applicability and direct system control. Radio coverage depends upon terrain, line-of-sight, antenna configuration and frequency. The FCC has allocated several frequency bands for fixed-station use. These include the low band (25-50 MHZ), mid band (75-76 MHZ), VHF band (150-174 MHZ), UHF band (450-512 MHZ) and the 900 MHZ band (928-960 MHZ). Each band has advantages and disadvantages, and the most frequently used is the UHF band because of channel availability. (Haught and Panguluri in Cotruvo, et. al., 1999) Spread spectrum radio transmission (902-928 MHZ) is another popular option. This type of radio was developed during world war II as a means to minimizing interference while maintaining message privacy by varying transmission frequency. (Mastran, 1999)

Instrumentation is arguably the most important, although often overlooked, aspect of a remote monitoring system. Instrumentation includes sensors used to obtain operating data from mechanical components. Any control instrumentation must incorporate digital or analog inputs as required. Digital inputs are used to control binary mode equipment such as motor starter relays, while analog inputs are used to control equipment such as variable frequency drives and variable speed pumps. Controllers may include power supply on/off, pressure, flow and chemical addition. Monitoring instrumentation must include standard analog output or digital outputs for current or voltage conditions. Monitoring may include pressure, flow, turbidity, pH and chemical concentrations. (Haught and Panguluri in Cotruvo, et. al., 1999)

The Taipei, Taiwan water system presents an example of the extensive use of telemetry to control water pressure, increase system operating flexibility, control leakage and improve emergency response time. The Taipei water system, as reported by Chu, serves a population of about 4 million across an area of approximately 16,000 hectares, and includes three purification plants, 12 booster stations, 30 storage units and over 2900 KM of distribution pipes. The telemetry system is hierarchically categorized into four sets of components: the central control center, substations, (12) booster station units and (92) remote terminal units. The following is a list of information obtained or facilities controlled by the telemetry system.

- water levels at the upstream storage reservoir dam and discharge weir
- water level at water storage units
- operating status of booster stations
- booster station pump control
- flow rates throughout the system
- distribution system pressures

The following system benefits are reported.

- easier water pressure variation accommodation
- network analysis to determine uniform pressure allocation
- increased operating flexibility
- decreased time to leakage detection
- system analysis based upon stored system data
- short-term and long-term water quality forecasting
- improved maintenance schedules based upon statistical operating analysis
- decreased operating time

1.2.3 Important Concepts: Risk and Economic Value

The multidisciplinary nature of the Project necessitated establishing Project-specific definitions for the interrelated concepts, *risk* and *value*. These definitions were motivated by the research goals and Project objectives, particularly the goal of understanding of risk in rural water systems and the objective of developing a model for evaluating cost effectiveness of remote monitoring as a risk-reduction method.

The strictly monetary definitions that have been established satisfy these needs and are based upon a multi-disciplinary (actuarial, economics and engineering) examination of these concepts. Although this subsection discusses the concept of risk as approached in three disciplines, the Project ultimately adopts a strictly engineering-based definition that differs explicitly from an actuarial- or economics-based definition. From the engineering perspective, risk is defined as the monetary value of potential or realized potable water loss, which occurs prior to delivery to customers, and value refers to any item to which monetary cost or price is attributed and recorded in system accounting records. This subsection summarizes the information utilized to establish these definitions.

The concept of risk is relevant to several disciplines, each of which applies a particular discipline-specific definition. (Zilberman, 1994) Disciplines within which the concept of risk is commonly encountered include actuarial or insurance, economics and engineering. From a standard dictionary definition of the English language, risk refers to the chance of injury or loss, and it is intuitively understood that risk refers in some way to future uncertainty. Although the definition applied may differ depending upon the context within which the concept is considered, there are three common elements: uncertainty, loss (potential) and linkage. Uncertainty is fundamental because risk can only exist when there is more than one possible future outcome; loss implies at least one of the outcomes must be negative or result in a less desirable system condition; linkage means that the loss must have an affect upon an individual or system. (Hampton, 1993)

The theoretical distinction between risk and uncertainty is considered to have been made explicit by Knight in his 1921 doctoral thesis, *Risk, Uncertainty, and Profit*, where he defines risk in terms of uncertain outcomes within a range of possibilities which are known or can be accurately estimated, and uncertainty in terms of situations where either the range of outcomes is unknown or the range of outcomes is known but the probabilities cannot be accurately estimated. (Spencer, 1974) According to Knight then, risk refers to situations that are characterized by adequate past experience, whereas uncertainty relates to situations that are essentially unique or about which there is little knowledge regarding significant aspects. However, in practical risk management these distinctions are of questionable usefulness; rather they tend to be effectively two extremes of a similar condition. (Corti in Wolfe, ed., 1973)

Risk management is concerned with identifying, controlling and minimizing adverse effects inherent in systematic activity. (Carroll, 1984) The goals of risk management depend upon the goals and operating requirements of the individual or organization. These may include long-term survival, long-term stability, cost control and social or ethical responsibility. Technological improvement can serve as a risk-reduction mechanism, particularly in projects with long expected lives where investment costs are temporally distributed. (Hampton, 1993)

Risk is defined by actuaries based upon efforts to identify, control and minimize adverse effects of unwanted events related to financial resources. In this discipline risk management usually means reducing to an acceptable level the average annual dollar cost from physical or intellectual property loss, primarily through identification of loss-causing conditions and portfolio adjustment through some combination of diversification and risk spreading. (Carroll, 1984)

Accordingly, risk or risk exposure refers to the magnitude or severity of potential loss facing an individual or organization as determined by the likelihood of loss and the potential size of each loss. Here, risk management deals with pure risks that are contingent and financial, i.e., those that that cause a decrease in monetary value but are not certain to occur. Exposure is defined as a condition that can cause loss, and hazards are conditions that increase the likelihood of loss occurrence. Typically, risk management for actuaries incorporates four approaches to deal with insurable risk: risk retention, risk avoidance, risk control and risk transfer. (Hampton, 1993)

Economists define risk based upon the concept of decision making under uncertainty. This uncertainty can be attributed to two sources. The first arises from questions about the accuracy of available information and the second from absence of perfect knowledge about future events. This means that consumer choice becomes a probabilistic exercise where consumer preferences are preferences for consumption probabilities, which in the simplest analysis can be described by an ex*pected utility* function based upon preferences that depend not only upon consumption levels, but also upon probabilities of each consumption level. Hence, consumers will make decisions of contingent consumption within their budget constraints, where contingent consumption bundles can be thought of as different probabilistic states. (Varian, 1996)

Von Neumann and Morgenstern are credited with publication of the initial work about consumer preferences under uncertainty in 1944. They showed that it is possible to construct a utility index that describes consumer behavior by assuming the results have been ordered in preference by the decision maker and that this ordering is transitive and complete. An additional requirement is that the decision maker is indifferent between equivalent choices regardless of the number of decision choices. This theory then specifies a standard gamble as a single-decision choice consisting of only the most and least preferable alternatives, with the probability *p* that the most desirable choice result will result. The decision maker's utility curve is developed by determining the value of *p* at which he is indifferent to the choice as the alternative to an available known result. After the decision maker's utility function is obtained, it is expected that he behaves rationally to maximize utility. (Buck, 1989) (Henderson and Quant, 1980)

This *expected utility model* regards decision making under uncertainty as a choice between alternatives that can be described as vector outcomes of income, wealth levels or utility x with a corresponding probability vector p, each with the dimension n. Decision makers are assumed to have a preference ordering of outcomes across the probabilities for which a number of axioms hold. Applying the preference or utility function $u(x_i)$ across the probabilities gives the summary measure $\sum u(x_i)p_i$, which is linear in probability but not necessarily in outcome. The utility function is assumed to be concave, implying risk aversion. (Buschena and Zilberman, 1994)

This concept of risk relates to the willingness of consumers to face a gamble for more wealth, which can be described by the curvature of the utility function. In such a gamble, by definition, the consumer also faces the possibility that wealth may decrease. Probabilities define the consumer's expected utility (of wealth) function, which is linear in accordance with the assumptions indicated previously, and his utility of expected wealth function, which is the locus of all points corresponding to the utility of each value of wealth. (Varian, 1996)

The expected utility model of consumer preference can be expressed as an expected utility function of the form

$$U(c_1, c_2, \pi_1, \pi_2) = \pi_1 v_1(c_1) + \pi_2 v_2(c_2)$$

which says that utility can be expressed as a weighted sum of some function of consumption in each consumption state $v_1(c_1)$ and $v_2(c_2)$, where the weights correspond to the probabilities π_1 and π_2.

A consumer is said to be *risk adverse* if he prefers to have the expected value of (current) wealth rather than face a gamble, which corresponds to a concave utility function. He is said to be a *risk lover* if he prefers to take a gamble, which corresponds to a convex utility function. He is said to be *risk neutral* if he is indifferent, which corresponds to a linear utility function where the expected utility of wealth is always equal to the utility of its expected value. (Varian, 1996) There is little distinction between this perspective and that of Friedman and Savage who argue that the second derivative of the utility function determines whether a decision maker is risk averse or risk loving. They describe a decision maker as risk averse at a particular income level x when $u''(x) < 0$, risk neutral when $u''(x) = 0$ and risk loving when $u''(x) > 0$. (Buschena and Zilberman, 1994)

Another way to describe choice under uncertainty is the *mean-variance utility model*, which can be thought of as a simplification of the expected utility model. This method relies on describing the probability distributions of the states of choice in terms of the distribution parameters: mean and variance. According to Varian, the mean-variance utility model is often employed when evaluating market risk allocation, where the optimal portfolio choice is established where the marginal rate of substitution (MRS) between risk and return is equal to the price of risk p or

$$\text{MRS} = (\Delta U/\Delta \sigma)/(\Delta U/\Delta \mu) = p = (r_m - r_f)/\sigma_m$$

where μ is the mean of the utility distribution,

σ is the standard deviation of the utility distribution,

r_m is the rate of return for risky assets,

r_f is the rate of return for risk free assets, and

σ_m is the standard deviation of or risky assets.

Even though the expected utility approach has been the primary approach to decision making under uncertainty in economics, recent developments indicate critical limitations. For example, it represents rational choices, and thus does not incorporate the impacts of anxieties and worry associated with random outcomes or choices, and consequently may not be a good model for assessing actual behavior patterns when these factors are relevant. (Buschena and Zilberman, 1994)

<u>The engineering definition of risk</u> derives from the fundamentals of system reliability or failure. In this context, *reliability* is defined as the probability that a system or component will function within specified limits for at least a specified period of time under specified conditions. This definition is

probabilistic and will often depend upon the relevant service period, which implies that the *distribution of the time to failure* is of fundamental import. (Aven, 1992)

The earliest documented formal reliability analysis was conducted by the mathematician Robert Lusser in connection with development of the V-1 missile during World War II. After evaluating the absolute unreliability of the first ten missiles, Lusser developed the *product law of reliability*, which states that the reliability of a system which functions only if all its components function equals the product of the reliabilities of the components. Lusser's work helped to improve the V-1's success rate to 60%. (Aven, 1992)

For any component or system the time-to-failure distribution can be characterized by the associated *instantaneous failure rate*: If $f(t)$ is the probability density of the time to failure of a given component (the probability that it will fail between time t and $t + \Delta t$), then the probability that the component will fail on the interval from 0 to t is given by

$$F(t) = \int f(x)\, dx$$

and the reliability function, expressing the probability that it survives to time t is given by

$$R(t) = 1 - F(t) .$$

A simple model describes risk by the consequence spectrum (K_1, F_1), (K_2, F_2),. . . , where the F_i designate the frequencies or probabilities of initiating events leading to the consequences K_i, as illustrated by Exhibit 1.1. Here the expected losses or risks are shown as the R_i and the total risk is the sum of the R_i. (Aven, 1992)

Thus the problem of dealing with risk is reduced to one of dealing with complete failures. In this context three questions are relevant: Which disasters are possible? What are their probabilities of occurrence? And what are the damages thus caused? Once these questions are answered, investment to reduce loss can be evaluated for effectiveness and cost effectiveness. Damages caused by system failures can be thought of as costs which may include replacement costs and compensation for loss of system or product availability. They may also include the monetary equivalent of subjective costs such as the perceived value of service or system interruption or the value of management's peace of mind. (Taylor, 1980)

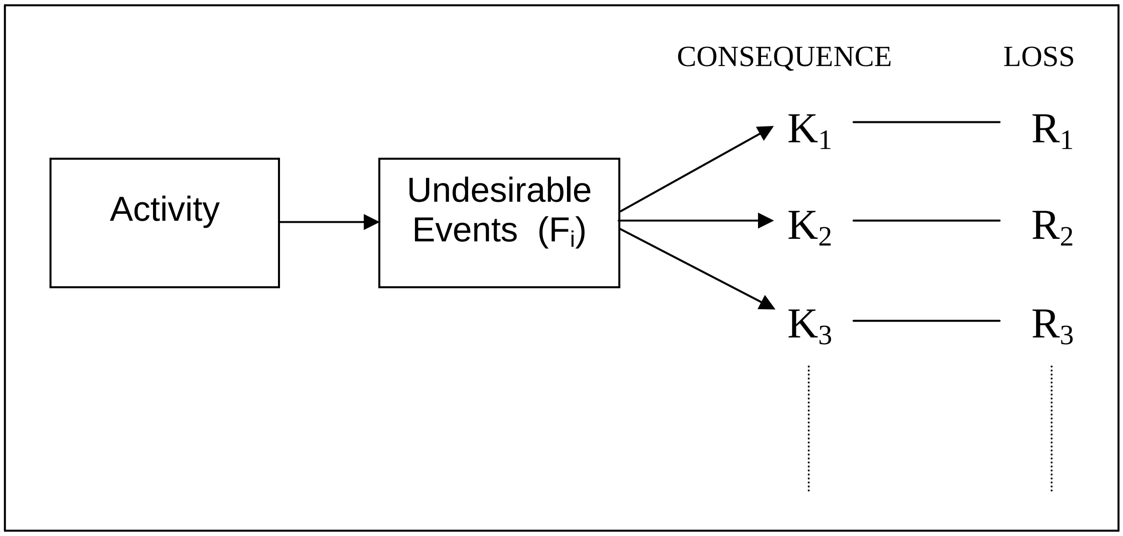

Exhibit 1.1. A general risk model from Aven (1992).

A simple model of risk in multi-component systems can be developed by considering each component numbered consecutively from 1 to n and operating in either a functioning state or a failure state. Then for the *i*th component we designate the binary variable x_i such that

$$x_i = 1 \text{ if the component is in the functioning state}$$
$$= 0 \text{ if the component is in the failed state.}$$

Additionally, we assume that the state of the system is determined completely by the component states, which allows us to define another binary function, the system structure function $\phi = \phi(x_i)$ where

$$\phi = 1 \text{ if the system is in the functioning state}$$
$$= 0 \text{ if the system is in the failed state.}$$

The structure function for a series system, which functions only if all components are functioning is given by

$$\phi(x) = x_1 \cdot x_2 \cdot \ldots \cdot x_n = \prod_{i=1} x_i \, .$$

The structure function for a parallel system, which functions only if at least one component is functioning is given by

$$\phi(x) = 1\text{-}(1\text{-}\ x_1)(1\text{-}\ x_2)\ldots(1\text{-}\ x_n) = 1\text{-}\ \prod^{n}_{i=1}\ (1\text{-}\ x_i)\ .$$

The expression on the right hand side is often written as $\coprod x_i$.

For example, the structure function for a parallel system with three components is

$$\phi(x) = 1\text{-}(1\text{-}\ x_1)(1\text{-}\ x_2)(1\text{-}\ x_3) = \coprod^{3}_{i=1} x_i$$

which is also written $\phi(x) = x_1 \coprod x_3$.

A model of system reliability can be established by assuming the state of each component is a stochastic variable and defining

reliability of the *i*th component	$p_i = P(x_i = 1)$,
unreliability of the *i*th component	$q_i = P(x_i = 0)$,
*r*eliability of the system	$h = h(\mathbf{p}) = P(\phi(\mathbf{X}) = 1)$, *and*
unreliability of the system	$g = g(\mathbf{q}) = P(\phi(\mathbf{X}) = 0)$.

Computation of system reliability for a for a series system is the product of the component reliabilities

$$h = P(\phi = 1) = P(x_1 = 1, x_2 = 1, \ldots, x_n = 1) = \prod^{n}_{i=1}\ P(x_i = 1) = \prod^{n}_{i=1} p_i\ .$$

Thus, if all components have equal reliability $h = p^n$.

This demonstrates that system reliability decreases rapidly with increasing system size. For example, with component reliabilities of 99 percent, a ten component system (n = 10) has system reliability h = 0.904, but if the number of components is increased to 50, h = 0.605.

Computation of system reliability for a parallel structure is done easily by taking the product of the component unreliabilities

$$g = \prod^{n}_{i=1}\ q_i$$

and the reliability is given by

$$h = 1 - \prod_{i=1} (1-p_i) = \prod_{i=1} p_i..$$

The reliability of an arbitrary series-parallel structure can be computed by using appropriate sequences the above formulae. (Aven, 1992)

Practical risk assessment usually proceeds using one of several methods. Among these, sensitivity and break-even analysis are two of the simplest, but have been historically demonstrated to be among the most effective. And although applied decision theory provides conceptually more sophisticated methods that may be useful in certain circumstances, the simpler methods dominate in practical application. (Fleischer, ed., 1975)

Sensitivity or break-even analysis, discussed in detail in Subsection 2.1.3, is a method for evaluating the merits of system operating alternatives whereby system response is observed as a function of input variable changes over a functionally significant range of input values. A determination is made whether system input and output variables will be within the range that encounters a *break-even point*, the operating condition at which a particular alternative becomes more cost effective. Break-even analysis is useful when there are multiple alternatives with output variables such as price, production volume or rate, fixed cost or total operating cost. In many cases it is appropriate to assume that output varies linearly with changes in these variables. Break-even analysis is in fact an application of the broader economic concept of marginalism, which has as it's logical corollary the tenet that economic activity should be increased as long as the marginal net gain is positive, i.e., where marginal gain equals marginal cost. (Ferguson and Shamblin in Fleischer, 1975)

Analysis using applied decision theory generally relies on one of five methods, maxi-min, Laplace, minimax regret (loss), maxi-max or maximum expected value. The basis of each of these methods is that the decision maker does not know with certainty the state that will result when he makes his decision. Here, the term state may be used variously to refer to states of nature, events or parameter values. Decision making under uncertainty then becomes an exercise in choosing among alternatives given this lack of knowledge, and is characterized by the decision maker's need to devise a strategy that optimizes his (perceived) benefit. (Fishburn in Fleischer, 1975)

The concept of economic value refers to the quantification of costs and benefits, usually in terms of monetary equivalent. It can be described as selection of definitions of *cost* and *benefit* to satisfy disciplinary convention or project intent. Fundamentally, economic valuation is an attempt to consolidate different value measurement systems into a common money-based system. (Ostwald, 1974) In practice, valuation is usually an attempt to quantify or objectify non-monetary or subjective items on a monetary basis for the purpose of enabling a direct comparison. (Thusen and Fabrycky, 1989) However, money and value are not the same concept. The concept of value is not an inherent property of an item, but rather can only be assessed by comparison with other items. Humphreys designates four types of value that may be distinguished.

- *Exchange value* is that which enables an item to be exchanged for money or other item.
- *Cost value* is the sum of material, labor and other costs to produce an item or service.
- *Use value* is the sum of properties and qualities possessed by an item.
- *Esteem value* is the sum of features of an item beyond that imparted by its functional use.

Different methods have been employed to address unquantifiable activity-related costs and benefits. Methods to ascribe monetary value to nonmonetary activities include *willingness to pay* and *willingness to accept* compensation for activity-related changes. Among the methods used to determine either of these typically employed in water resources projects are indirect methods such as *travel cost* and *hedonic pricing*, and the theoretically direct method, *contingent valuation*. Contingent valuation derives a willingness to pay by surveying affected parties' preferences for goods and services. Willingness to pay is then used to establish a monetary estimate of benefit that can be utilized in a benefit-cost analysis. This technique has been used for numerous water-related projects including an assessment of water supply reliability in California. (Dinar and Zilberman, 1991) (Pearce and Turner, 1990)

Although these methods exist, it is important to recognize that it is not always possible to value costs or benefits from public projects in monetary terms. In these cases it is imperative that any such costs or benefits be adequately represented in terms most meaningful to the affected parties and those performing the evaluation. When such non-quantifiable costs or benefits are present, a useful benefit-cost analysis not only compares quantifiable consequences but also represents nonquantifiable consequences in useful terms. (Pearce and Turner, 1990)

<u>*Multicriteria decision analysis*</u>, or multicriteria decision making (MCDA) is a method useful for conveying consequences that are not quantifiable in monetary terms. Broadly speaking, MCDA is utilized to evaluate situations with conflicting and incommensurate criteria. There are several categories of MCDA problems that can be classified on the basis of three dichotomies: (1) multi-

objective decision making versus multi-attribute decision making, (2) individual versus group decision making, and (3) decisions under certainty versus decisions under uncertainty. Until recently MCDA problems generally assumed spatial homogeneity even though this produced unrealistic models. With the advent of GIS, this assumption is no longer necessary and it is possible to employ *spatial MCDA*.

The Project adopts a strict definition of risk based upon the engineering perspective, where risk is defined as the monetary value of potable water loss. This risk is inherent in water systems and is realized during operating excursions. The magnitude of such risk is a function of the unit cost of water and the aggregate duration of operating excursions. With this definition, the total risk inherent in a water system can be thought of as the total value of potable water produced or the total system operating cost. In practice, it is more useful to consider only that portion of water loss typically realized as described by historical operating records. This then gives the maximum risk or potential for risk reduction inherent in the system.

The Project also adopts a purely monetary definition of value that considers only financial costs and benefits. Most important among these costs and benefits is the monetary value of water loss that becomes a principal variable in the simulation model. This definition of value is intentionally limited to give a manageable relevant Project scope, but other valuation systems can be established by redefining costs and benefits by using different methods of valuation.

1.2.4 Fiscal Fundamentals: Accounting, Economic Equivalence and Cost Categorization

Three interrelated fundamental concepts that must be understood for cost modeling are addressed in this subsection. *Accounting* enables understanding the financial condition of a business or public entity by providing a common system of reporting procedures that describe the entity's resources, debts and transactions. *Economic equivalence* refers to the need to adjust prices or costs to compensate for the time value of money. *Cost categorization,* necessary for accurate cost modeling, refers to the description of operating costs in accordance with the nature of their associated inputs as either fixed or variable.

<u>Accounting</u> is the means by which the monetary transactions of an entity are recorded, categorized and reported on devices that include periodic balance sheets and income statements, usually based upon double-entry bookkeeping. In addition to summarizing an entity's status in terms of assets and

liabilities, an accounting system provides historical data that may be useful for various types of financial or economic analyses.

Accounting entries are made to represent debits or credits, which give rise to assets or equities, and which must be equal or balanc*e*. The fundamental accounting equation is given by Ostwald as

$$\text{Assets} = \text{Liabilities} + \text{Owner's Equity} = \text{Liabilities} + \text{Net Worth}$$

or

$$\text{Assets} = \text{Liabilities} + \text{Net Worth} + \text{Income} - \text{Expenses}\ .$$

Assets are those things of monetary value owned by the entity, and may be categorized into current assets, fixed assets and intangible assets. Current and fixed assets are tangible assets such as inventory accounts or equipment and non-depreciated property. Intangible assets are those assets such as trademarks and patents. Liabilities are debts of the entity, and may be categorized into current and long-term debt. The net worth of an entity is the ownership interest in its net assets, which in the simplest case consists of capital stock and surplus or retained earnings. Broadly, capital stock is the portion of net worth paid in by owners, and surplus or retained earnings is that portion of the net worth accumulated from the excess of profits earned beyond dividends paid. In certain situations the concepts of proprietorship or capital assets replace net worth. (Ostwald, 1974)

Income represents revenue generated prior to deduction of costs, and expenses represent the costs of engaging in the activity of the entity. A profit and loss statement indicates the entity's incomes and expenses over a period of time. Most accounting is done on the accrual basis where incomes and expenses are recorded when they are earned or incurred. Accounts are also adjusted for deferred expenses, depreciation and bad debts before synthesizing the information into balance sheets and income statements. The balance sheet is a tabular presentation of the important accounting information: assets, liabilities and net worth, in itemized format. The income statement is also variously referred to as statement of earnings, profit and loss statement or income and expense statement. It shows the net profit or loss, which represents the net change in net worth during the reporting period. (Ostwald, 1974)

Working capital, investments and depreciation are important types of accounting entries. Working capital comprises funds, in addition to fixed capital and startup expenses, necessary to initiate a project and meet subsequent obligations. For a production facility, this may include accounts payable, accounts receivable, cash on hand, raw materials and supplies and inventory. Insurance on machinery is generally considered inventory and is transferred to an inventory account. (Humphreys, ed., 1984)

Investments are treated as changes in the asset or liability condition of the entity. Most accounting systems consider the cost of assets as prepaid operating expenses that are charged against profits throughout an appropriate period of time. Accounting systems also provide depreciation charges that must be understood for proper investment decisions. (Humphreys, ed., 1984)

A great amount of confusion and ambiguity exists about depreciation, not in small part due to political influences. Simply, depreciation is an accounting charge that provides for recovery of capital used to purchase physical assets. It functions by allocating an amount of money that represents the cost over the recovery life of a tangible capital asset in a systematic and consistent manner, whereas the initial investment is usually charged as a prepaid operating cost that is allocated to an expense account. (Ostwald, 1974) Depreciable property is a physical asset that is held for the purpose of obtaining income and has a useful life of more than one year, and a depreciation schedule is a means of allocating the expenditure as an expense over the years. (Humphreys, ed., 1984)

The accounting rules and techniques developed over the centuries have been arranged into guidelines, which in the United States comprise the *Generally Accepted Accounting Principles* or *GAAP*, which summarize generally accepted accounting rules, procedures and principles. The purpose of formulating GAAP was to standardize accounting rules so that everyone using accounting information could be in agreement as to the meanings of the information and could then consistently interpret it. More specifically, financial statements for public entities are prepared in accordance with GAAP as applied to government units per accounting and financial reporting principles established by the Governmental Accounting Standards Board. Additionally, in Virginia, financial statements and audits for public entities are also governed by specifications for auditing counties, cities and towns issued by the Auditor of Public Accounts of the Commonwealth of Virginia. (Hicok & Fern, 1998)

Economic equivalence must be considered when performing cost or economic analysis because comparison of alternatives requires that all cash flow amounts, times of occurrence and interest rates be converted to an equivalent basis so that real differences can be compared. Equivalence methods for evaluating alternatives include worth measures and efficiency measures. The most common measures are *present worth*, *future worth*, *annual worth*, *capitalized amount*, *rates of return and return on investment*. Because they are related, the measure selected is often a matter of preference, although in some cases the nature of the problem may dictate applicability. The Project uses the *present-worth* or *net present-worth* method. This method is based upon converting all cash flows during the analysis period to an equivalent present value using a selected interest rate. For some analyses it will be important to know the relationship between the present-worth method and other equivalence methods because a firm's financial records may include more than one method. The remainder of this discussion on economic equivalence is adapted from a forthcoming chapter on engineering economics by Wetzel.

The *future-worth* method is based upon converting all cash flows from the proposed investment during the analysis period to an equivalent future (end of period) value using a selected interest rate. The future-worth amount can be computed by multiplying the present-worth amount by the appropriate single payment compound-amount factor.

The *annual-worth* method is based upon converting all cash flows during the analysis period to an equal-payment series. This method is referred to more generally as the *periodic-worth* method because the period may be any unit of time, but the method is usually employed on an annual basis. The annual-worth amount can be computed by first calculating the present-worth amount and multiplying it by the appropriate equal-payment series capital recovery factor.

The *capitalized-amount method* is a special case of the present-worth method based upon the assumption that cash flows continue perpetually. The capitalized amount is the present worth of cash flows necessary during an infinite-duration analysis period (or the present amount of money that will provide the necessary cash flows for perpetuity at the applicable interest rate). The capitalized amount can be computed by first calculating the annual-worth amount for an infinite analysis period followed by converting this to a present amount by multiplying by the appropriate equal-payment series present-worth factor. This also means that the capitalized amount is equal to the infinite analysis period annual-worth amount divided by the interest rate.

The present-worth, future-worth, annual-worth and capitalized-amount methods are consistent bases of comparison and will give the same decision result in any alternative comparison. Given any two alternatives A and B evaluated with the same interest rate the following is true.

$$\frac{\text{present worth}_A}{\text{present worth}_B} = \frac{\text{future worth}_A}{\text{future worth}_B} = \frac{\text{annual worth}_A}{\text{annual worth}_B} = \frac{\text{capitalized amount}_A}{\text{capitalized amount}_B}$$

Price level changes, particularly inflation, may need to be included in the economic analysis. Because it is the relative price level changes that will impact an alternatives analysis, if all factors experience similar inflation there is no need to make adjustments. Several indices are available to enable calculating inflation for the particular type of goods or services under consideration. Two indices commonly utilized to adjust for inflation are the Consumer Price Index (CPI) and the Producer Price Index (PPI). For studies involving engineered systems, particular indices or methods should be used that reflect price level changes for the specific category of goods or services.

The *time value of money* refers to the ability of invested money to earn more money over time by accruing *interest*. The rate at which the capital earns interest is termed the *interest rate*. The term interest can be thought of as money earned by the original amount, the *capital,* or as the amount charged by a financial institution for use of borrowed capital.

Economic analyses are based upon *cash flow*, the occurrence of receipts and disbursements over time. Sets of cash flows are *indistinguishable* if the net cash flows during each period are the same regardless of interest rate; they are *equivalent* if they have the same worths at a given interest rate.

Interest is usually charged (accrued) at the end of each interest period. Interest not paid at the end of each period is *compounded*, and subsequent interest charges are based on the new balance. Cash-flow factors or *compound-interest factors* enable conversion of one type of cash flow to any other, such as conversion of a single payment at a particular time to an equivalent equal-payment series of payments or conversion of an equal-payment series of payments to an equivalent single payment at a particular time. The following symbols will be used to facilitate discussion about cash flows and interest formulas.

P = a present principal sum of money (at the beginning of the first interest period)

i = the periodic interest rate

n = the number of interest periods

A = a single payment, in a series of n equal payments, made at the end of each period

F = a future sum of money after n periods (at the end of the last period)

With *simple interest*, the total repayment amount is equal to the principal plus the simple interest, which is proportional to the length of time the principle is borrowed in accordance with $I = Pni$, where I is the simple interest amount.

With *compound interest*, for a single cash flow where P is invested at the beginning of n periods, the *present worth* P and *future worth* F are described by

$$F = P\,(1+i)^{n} \quad \text{or} \quad P = F\,(1+i)^{-n}\ .$$

The growth multiplier $(1+i)^n$ is called the *single payment compound-amount factor*, and the discounting multiplier $(1+i)^{-n}$ is called the *single payment present-worth factor*.

Manipulation of either the single payment compound-amount factor or the single payment present-worth factor gives the interest formula

$$i = (F/P)^{1/n} - 1\ .$$

In addition to single payment, cash flow is typically categorized into three general types: equal-payment series, gradient series and continuous. Equal-payment series and gradient series are characterized by discrete compounding and discrete payments in accordance with a constant interest rate, whereas continuous cash flow is characterized by continuous compounding and payments. Continuous compounding discrete payment cash flows are also possible but seldom used.

The formulas for each cash flow type can be derived by mathematical manipulation of the single payment compound-amount factor $(1+i)^n$. However, this is seldom done in practice and computations are typically facilitated by the use of compound-interest factor tables that provide multiplication factors as a function of interest rate and number of payment periods.

The *equal-payment series* (also called uniform series or annuities) are those for which equal payments are made at equal time intervals, this interval being termed the payment period. The four most common equal-payment series cash flow factors are compound amount, sinking fund, present worth and capital recovery.

The *equal-payment compound-amount factor* F/A when multiplied by the payment amount gives the single equivalent value (compound amount) at the end of the series:

$$F = A\,[\{(1+i)^{n} - 1\}/i]\ .$$

The *equal-payment sinking-fund factor A/F* when multiplied by the compound amount gives the end of period payment amount. It is the reciprocal of the equal-payment compound-amount factor:

$$A = F\ [i/\{(1+i)^n\ - 1\}]\ .$$

The *equal-payment present-worth factor P/A* when multiplied by the payment amount gives the single equivalent value (present amount) at the beginning of the series (time = zero):

$$P = A\ [\{(1+i)^n\ - 1\}\ /\ i(1+i)^n]\ .$$

The *equal-payment capital-recovery factor A/P* when multiplied by the present amount gives the uniform end of period payment amount such that the amount remaining at the final payment is zero. It is the reciprocal of the equal-payment present-worth factor:

$$A = P\ [i(1+i)^n / \{(1+i)^n\ - 1\}]\ .$$

The relationships between equal-payment series and gradient or continuous compounding briefly described here are based upon discrete compounding and cash flows. *Gradient series* are those for which payments, made at equal time intervals, differ from each preceding payment by a fixed amount or constant multiple. Gradient series in which payments differ by a fixed amount are termed *uniform-* or *linear-* or *arithmetic-gradient series* and the difference between payments is termed the *gradient* (*G*). Gradient series in which payments differ by a constant multiple are termed *uniform-rate* or *geometric-gradient series* and the constant is termed the *rate of increase* (*g*).

Problems involving equal-payment series and gradient-series cash flows can be solved using the applicable equations or by using compound-interest factor tables that provide values of single-payment, uniform-series and gradient-series payment factors as a function of interest rate and number of payment periods. These tables can be accessed in text and reference books dealing with engineering economics, financial analysis or related subjects.

Continuous cash flow methods require understanding the concepts of *nominal and effective interest rates*. These interest rate concepts are also important for analyzing problems where interest rates are specified with other than annual interest-rate periods. Interest rates or rates of return have meaning only when specified with associated time periods, and although they are generally stated with implicit annual periods, other compounding frequencies may be used such as quarterly, monthly or daily. When an interest rate is specified with an interest period other than one year, convention is to state the nominal (annual) rate and the interest period. More frequent than annual compounding results in an effective rate that is greater than the nominal rate. When compounding is annual, the nominal and effective rates are the same.

The nominal rate r only approximates the effective interest rate and is equal to the interest rate per period i times the number of periods per year m. In transactions conducted in accordance with the Federal Truth in Lending Act the nominal rate is termed the *annual percentage rate* (APR). The effective annual interest rate i_e is the annually compounded equivalent rate corresponding to a nominal rate

$$i_e = (1+i)^m - 1$$

where: i = periodic interest rate (r/m).

Effective interest rate is a concept that allows comparing interest rates that are specified with dissimilar interest periods. For example, in accordance with these conventions, a loan given at "six percent compounded monthly" has a nominal rate of six percent with twelve compounding periods per year. Hence, for this loan the periodic rate is one-half percent and the effective rate is 6.17 percent.

Continuous-compounding discrete cash-flow factors can be derived by substituting the effective rate for continuous compounding $e^r - 1$ into the discrete-compounding cash-flow factors. Thus the *continuous-compounding single-payment compound-amount factor* is e^{rn} and the *continuous-compounding single-payment present-worth factor* is e^{-rn} where n = number of annual periods. Thus for continuous-compounding discrete cash flows

$$F = Pe^{rn} \quad \text{or} \quad P = Fe^{-rn} \; .$$

The continuous-compounding cash-flow factors can be defined with the effective interest rate rather than the nominal interest rate, although this is seldom necessary.

Cost categorization is necessary to permit accurate economic modeling. Costs are categorized based upon their associated production inputs as either fixed or variable, the sum of which is the total cost of production for a given short-run production period.

The *short run* is a period of time too brief to allow production capacity to be altered by incorporating additional indivisible inputs. In the short run, production can be varied only by changing variable inputs or production intensity. In contrast, the *long run* is a period of time long enough to allow changes to indivisible inputs that increase production capacity as may be accomplished by installing additional equipment. The long run is thus the minimum period of time within which all production inputs can be varied. In the long run, production can be varied by changing production intensity and capacity. An annual production period is frequently selected for economic analyses because the short run is usually defined as one year and because this gives coincident accounting and production periods. (Doll, 1978)

The classification of costs as *fixed* or *variable* is a function of both the length of the production period and the extent of indivisibility over the range of output under considereation. Typical fixed costs might include interest on debt, rent, insurance premiums, salaries and depreciation, whereas typical variable costs might include payments for materials, fuel, power and transportation. (Henderson and Quandt, 1980)

Because accounting records do not explicitly distinguish fixed and variable costs, accounting entries must be deciphered and categorized based upon the nature of each production input within the short-run production period relevant to the analysis. Certain fixed costs ascribable to a production period, particularly those representing the value of indivisible assets such as those that comprise a physical plant, will not be explicitly identified as such on accounting records, but rather must be extracted from the records in a manner that depends upon specifics of the accounting methods. This is particularly relevant when considering depreciation and capital funding. For example, where depreciation is funded the sum of annual accounting entries for depreciation can be used to represent the annual value of the fixed plant. But where depreciation is not funded, as is the case with many public entities, other entries must be selected to represent this value. In this case one alternative is to use the sum of principle payments on debt and insurance to represent the value of the physical plant.

Part II – Parametric Simulation Cost-Effectiveness Model

2.1 Background and Fundamental Concepts

2.1.1 Introduction

The parametric simulation model developed to satisfy the Project objective performs a *break-even analysis* to determine *cost effectiveness* of remote monitoring for rural water supply systems by simulating operating costs for a specified water system with manual or remote monitoring. The model cost functions are based upon the assumptions, hypotheses and general cost functions presented in this section. After discussing the fundamental concepts parametric cost estimating and cost effectiveness in subsections 2.1.2 and 2.1.3, respectively, the hypotheses specifying the economic framework of the model that led to the general form of the cost functions are presented and the cost functions are developed in Subsection 2.1.4.

2.1.2 Parametric Cost Estimating

Estimating is defined by the National Estimating Society as "the art of approximating the probable worth or cost of an activity based on information available at the time." (Stewart, 1982) More specifically, cost estimating is an attempt to forecast of the cost of an endeavor, with a specified or implied accuracy, through judgment that may rely upon historical information and predictive tools such as mathematical models. Parametric cost estimating involves the correlation of historical data through various techniques, the selection of which depends upon several factors including characteristics of available data. According to the Parametric Estimating Handbook, parametric cost estimating was pioneered by the Rand Corporation in the early 1950s as part of an effort to support high-level planning studies for the United States Air Force by developing cost estimates for first- and second-generation intercontinental ballistic missiles and jet aircraft based upon speed, range and other design parameters. (Birkler, Garfinkle and Marks, 1982) (ISPA, 1999)

The technique most commonly utilized for parametric cost estimating is the cost-estimating relationship (CER), which relates cost as a dependent variable to one or more independent cost-diving variables or parameters by correlating historical cost data with technical non-cost data, where the non-cost variable is typically related to system size or operational characteristic. (ISPA, 1999) The most widely utilized type of estimating relationship is the linear CER. (Stewart, 1982) Cost data are generally obtained from the entity's general ledger and other accounting or other financial records. Technical non-cost data are usually obtained from the appropriate design or operating records. A fundamental requirement for the non-cost variable is that it be a significant predictor of cost: it must be a *primary cost driver*. Data issues are often of great concern when utilizing parametric estimating because data characteristics determine accuracy of the CER. (ISPA, 1999)

After selecting appropriate data, routine normalization is performed to remove effects of temporal changes in the value of money and the effects of any production changes during the period of record. Adjustments may also be necessary to assure consistent definitions, format, scope and temporal context, and to address comparability problems and anomalies. According to the Parametric Estimating Handbook data should be reworked for the following. (ISPA, 1999)

- Data category definitions must be consistent.
- Data formats must be consistent.
- Data must be based upon projects or activities of similar scope.
- Temporal changes and other incomparable definitions of variables must be eliminated.
- Data must be adjusted for unusual events or conditions that do not reflect the relationship between the cost and non-cost variables.

Reliance upon parametric techniques by government and industry today is illustrated by the fact that many organizations have experienced parametricians on staff who regularly employ parametric cost estimating. (ISPA, 1999) For example, RACER (Remedial Action Cost Engineering and Requirements System) is a widely utilized parametric cost-estimating model that has been engaged by the U.S. Army Corps of Engineers to estimate environmental remediation projects, including site investigations, remedial designs, remedial actions, and operations and maintenance activities, totaling over $10 billion. Rast reports that RACER estimates costs at three levels, the order-of-magnitude level with accuracy of +50 to –30 percent, the budget concept level at +30 to –15 percent and the definitive level at +15 to –5 percent. Another example, described by Meist is a model developed for design studies, budgetary forecasting and cost-benefit analyses that determines development and production costs for solar space and dynamic isotope power systems. This model employs about fifty CERs that project costs as functions of design and technology conditions such as power level, power storage requirements and photocell construction type.

2.1.3 Cost Effectiveness and Break-Even Analysis

The economy of variation of operating activities for a production facility can be described by an appropriately constructed input-output curve that illustrates the relationship between input as total operating cost and production intensity. In the general case this curve is not linear and does not intersect the origin. The non-linearity resulting from functional system characteristics and the law of diminishing returns that acts upon variable costs. For the most general short-run case, unit fixed cost will decrease with increasing production, whereas unit variable and total costs will increase after reaching a minimum due to efficiency changes. (Taylor, 1980)

Incorporating the assumption of constant load or efficiency into the form of an input-output relationship results in a linear function. This functional form implies that output is varied by varying operating time and associated variable inputs, while fixed inputs remain constant. Incremental cost can be defined as the increase in variable cost due to a unit change in output. This is the concept of marginal cost or instantaneous slope of the input-output curve. In general, incremental cost varies along the operating curve due to changes in operating efficiency, but is constant for a linear input-output function where the incremental cost and variable cost are constant and equal. (Taylor, 1980)

Weiser examined the relevance of the linearity assumption in the context of break-even analysis and reports that the linearity assumption can be considered a short-run concept in contrast to the long-run concept where marginal costs increase after an initial decline. Among the empirical evidence cited to suggest that within normal output ranges constant unit costs are a reasonable expectation is a study by Dean which indicates that the "…curvature would be so slight… that it could scarcely affect any economic conclusions…." Although Weiser cautions that "…while relying upon the linearity assumption, users must "…be careful to designate the relevant range [of production]."

Empirical studies into economies of public water systems give information about the expected shape of the input-output curves in such facilities. A study by Bourcier and Forste into ten water supply firms in the Piscataqua River Watershed based upon production and distribution costs led to a suggestion of two pricing polices. The first would charge an average price to cover fixed and variable costs and the second would charge an average price to cover fixed, variable and investment costs. A study by Bailey and Long published in a University of Idaho Agricultural Experiment Station Research Bulletin into costs of water production and distribution in Idaho concludes there is a "reasonably high" correlation (0.70 to 0.81) between water production (delivery) and total cost based upon least-squares regression.

Cost analysis refers to comparing values of alternative systems for producing a desired outcome. Various approaches to cost analysis, each with different advantages and disadvantages, include cost effectiveness, cost benefit, cost utility and cost feasibility. Cost-effectiveness analysis is a method to compare the worths of alternatives with similar objectives that originated in the economic evaluation of complex defense and space programs but can be applied in a variety of situations. While cost effectiveness is unlikely to be the sole criteria when evaluating alternative systems, it is likely to be one of the more useful. (Thuesen and Fabrycky, 1989)

Cost-effectiveness analysis considers both costs and benefits of alternatives. Three conditions must be satisfied to enable the use of cost-effectiveness analysis: (1) There must be a set of common objectives. (2) There must be alternative means for achieving the objectives. (3) It must be possible to bound or accurately define the alternatives being evaluated so that the cost of each can be accurately determined. (Thuesen and Fabrycky, 1989)

The need for a formalized well understood cost-effectiveness method and appropriate application of the results is addressed by Enthoven.

> Although the general concept of cost effectiveness seems intuitively obvious, the specific detailed techniques can be highly esoteric. Intuitive common sense can be treacherously deceptive. For example, while statements proposing the simultaneous maximization of effectiveness and minimization of cost may be emotionally satisfying, they are senseless because simultaneous satisfaction of the two goals is impossible. Cost-effectiveness evaluations give information that [is] useful only when considered in context.

Cost-effectiveness analysis includes three preliminary steps. The first is to define the system to be analyzed. The second is to designate alternatives that can accomplish the objectives. The third is to establish the evaluation criterion and method. Typical effectiveness criteria are benefit, gain, utility and worth. But other more easily quantifiable measures are typically used such as operating rate, availability or reliability. After an effectiveness criterion is selected, an appropriate cost-effectiveness method can be selected. (Tuesen and Fabrycky, 1989)

Break-even analysis is a useful method for describing cost effectiveness when alternatives with different levels of capitalization are considered. For most systems one such alternative will be more economical in one operating range and another alternative will be more economical in another range. A break-even model can be designed to compare alternative systems by characterizing total system operating costs as functions of a common operating variable such as operating rate. Such analysis will reveal the operating rate beyond which one alternative will result in lower total operating cost. The analysis can be performed algebraically or graphically. In either case it is convenient and generally sufficiently accurate to assume that the pertinent cost functions are linear. (Ferguson and Shamblin in Fleischer, 1975)

One of the most salient pieces of information provided by break-even analysis is the break-even point (or indifference point). This can be defined equivalently as the intersection of the alternative total cost functions or as the value of the operating variable at which either alternative results in the same system operating cost. For values of the operating variable below the break even point the less capital intensive alternative results in a lower total operating cost, and for values of the operating variable above the break even point the more capital intensive alternative results in a lower total operating cost. (Ferguson and Shamblin in Fleischer, 1975)

Exhibit 2.1 illustrates the results of a hypothetical break-even analysis where the total operating cost for each alternative varies linearly with operating rate. The break-even point for this example occurs at an operating rate of approximately 670 units per day. Alternative 1, which might represent operation with existing equipment, is more economical at daily operating rates less than 670; and alternative 2, which might represent operation with additional capital investment, is more economical at daily operating rates above 670. This example can be solved mathematical using the following variables.

C_1 = total cost of alternative 1
F_1 = fixed cost of alternative 1
R_1 = unit operating variable cost for alternative 1
C_2 = total annual cost of alternative 2
F_2 = fixed cost of alternative 2
R_2 = unit operating variable cost for alternative 2
X = production rate where both alternatives have equal total cost (break even)

Because the break-even point occurs were the total costs are equal we have

$$C_1 = C_2$$

and because

$$C_1 = F_1 + R_1X \quad \text{and} \quad C_2 = F_2 + R_2X$$

we obtain

$$F_1 + R_1X = F_2 + R_2X$$

from which it follows that

$$X = (F_2 - F_1)/(R_1 - R_2) \ .$$

For the example presented, this gives the same result as the graphical solution.

$$X = (21.0 - 12.3)/(.055 - .042)$$
$$X = 669 \ \ (670)$$

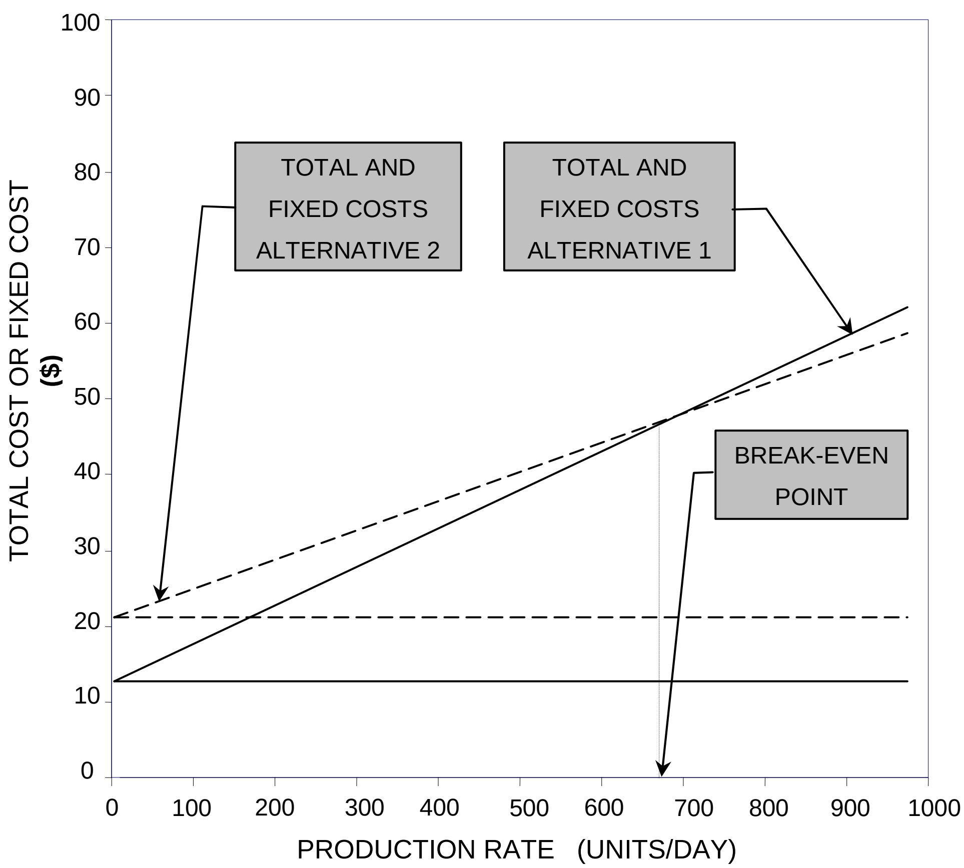

Exhibit 2.1. Example break-even analysis chart for two operating alternatives showing fixed and total operating costs as functions of production rate.

The changing economy of alternatives at different operating rates reflects the inverse relationship between fixed cost and variable cost. Additional capital investment, represented in fixed cost, generally creates more efficient operating conditions resulting in lower unit variable cost, but total cost does not decrease until the operating rate is high enough for decreased variable cost to offset the additional investment. Thus the break-even point indicates the production rate above which a specified capital investment will lower the total unit cost or above which it will be *cost effective*.

Another method frequently used to evaluate potential investments is the payback method. This method, most often employed for small investments, emphasizes concern for liquidity by describing the rapidity with which investment capital is recovered. The period of time, in years, necessary for the benefits from an investment to equal the cost of the investment is defined as the payback period, which is equal to the initial investment divided by net annual saving. Simply stated, the payback period is the time required for the benefits from an investment to equal the investment cost.

Even though simplicity and emphasis on funds availability make the payback method the most used investment rating method in the United States industrial sector for small investments, it can lead to spurious conclusions and detrimental recommendations when employed without elaboration due to certain inherent characteristics. Primary among these are exclusion of interest, depreciation and savings effects beyond the payback period. Also, financial data typically utilized are not discounted and salvage values are not included, so depreciation and interest effects are ignored, and although the concept can be extended to include depreciation and discounted vales, in the vast majority of cases it is employed in its simplest form. (Kurtz, 1984) (Riggs, 1982)

The payback method is a simple method that is not an exact economic analysis, so a shorter payback period does not imply that an alternative is a preferable investment. It is also an approximate method in which costs and benefits are considered without timing and in which all economic benefits beyond the payback period are ignored, which makes it biased against investments with greater deferred income. Because the method does not describe the overall profitability of an investment it should not be considered an alternative to a rigorous economic analysis, but it can be useful as a companion method, particularly when liquidity or rapidity of capital recovery is important. When a suitable cost-effectiveness method and the payback period method are used together, the information provided is often sufficient to enable decision makers to exercise judgement. (Kurtz, 1984) (Newman, Lavelle and Eschenbach, 2002)

2.1.4 Economic Framework: Hypotheses and Cost Functions

The parametric simulation model calculates water supply system total operating costs as functions of operating rate in accordance with the equations developed based upon two sets of assumptions: those regarding the economic framework under which water systems operate and those regarding the three subsystems comprising these systems. The assumptions about the economic framework are those of pure neoclassical microeconomic theory under static certainty, with simplifications regarding the mathematical functions necessary to accommodate undeterminable variable behavior, which are in all cases assumed to be linear.

The economic framework assumptions are categorized into those regarding characteristics of the mathematical functions, the decision agent and the market structure.

Mathematical functions:

- are mathematically analyzable – single valued and continuous (although not with continuous derivatives)
- cost functions are linear (or step linear for multiple systems)
- represent technically efficient systems
- are based upon static analysis

Decision agent:

- figures rationality
- operates to minimize risk (cost) under constraint of cost effectiveness
- possesses perfect knowledge

Market structure:

- water systems are government agencies - not perfectly competitive
- other factors of production are perfectly competitive
- known distribution of resources and property
- fixed institutions and human nature
- absence of externalities as a source of market failure

There are four sets of assumptions about risk and the three subsystems comprising water systems. In general, these maintained hypotheses describe static water systems in terms of the risk and water system conditions during any model simulation. In other words, a simulation represents a specific period of time during which the subsystems and risk conditions do not change, except to accommodate changes associated with incorporating remote monitoring and to simulate one water system replication as a means to observe a break-even point that may occur beyond the existing water system capacity.

Most of the maintained hypotheses and the manner in which the subsystems and risk conditions change can be inferred from the cost functions. The maintained hypotheses as listed here generally apply to the subsystems and risk conditions during any model simulation; i.e., the conditions specified will vary to simulate to simulate changed (manual versus remote) and water system replication. Exceptions are noted with (always).

Physical subsystem:

- mechanical systems are fixed
- geography and general infrastructure are fixed (always)
- geography is similar to that of western Virginia counties (always)
- geographic information is readily available (always)

Operational/personnel subsystem:

- operational/personnel subsystem is fixed

Fiscal subsystem:

- all costs known (perfect knowledge) (always)
- variable costs increase linearly (always)
- marginal cost is constant
- cost of realized risk is described by past events (always)

Risk:

- sources and probability of risk are determined by past events (always)
- risk probability and magnitude are invariant

For the simplest analysis of two operating alternatives for a specified water system, two total cost functions describe the cost of water delivered as functions of delivery rate for either manual or remote monitoring. The difference between these total cost functions is based upon two fundamental conditions. The first is that fixed costs are greater with remote monitoring than with manual monitoring, and the second is that unit variable cost is less with remote monitoring than with manual monitoring due to improved delivery efficiency.

These conditions imply cost functions of the form

$$TC = CF + vQ$$

where TC = total operating cost,
CF = fixed cost,
v = variable cost/unit water delivered, and
Q = water delivery rate.

This gives average cost functions of the form

$$AC = CF/Q + v$$

and marginal cost functions of the form

$$MC = dTC/dQ = v\ .$$

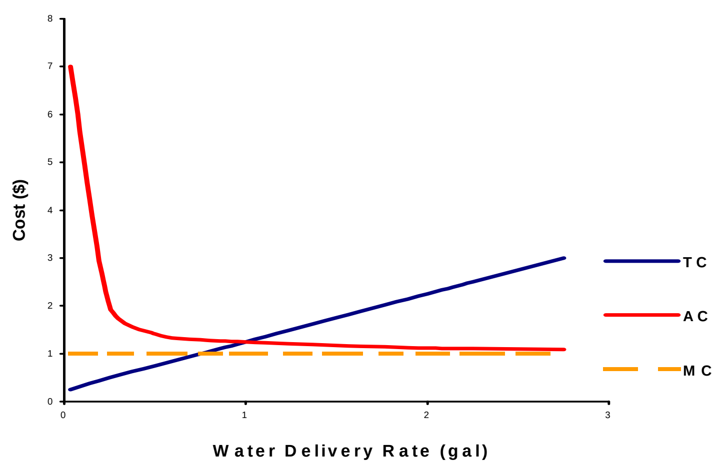

Exhibit 2.2. Cost function form for single water system.

The general relationships between the total cost, average cost and marginal cost functions for either monitoring mode are illustrated by Exhibit 2.2. With water delivery rate as the independent variable, total cost begins at its intercept with fixed cost (.25 in the example) and increases linearly with slope equal to v, the unit variable cost (1.0 in the example); the average cost function decreases asymptotically toward the marginal cost; the marginal cost is a constant value equal to the unit variable cost and is always below the average cost.

The multiple water system case represents a replicated water system with assumptions otherwise similar to the single system case. For either monitoring mode, this results in an aggregate total cost function that consists of a set of individual cost functions. The aggregate cost functions, described below and illustrated in Exhibit 2.3, are termed step linear because individual cost functions are linear and the aggregate function steps up by an amount equal to the additional fixed cost at water delivery rates where replications occur. With Q defined as the single system capacity, and other terms as above, these cost functions are of the form

$$C = F + vQ \qquad (\text{for } 0 < Q \leq 1)$$
$$C = 2F + vQ \qquad (\text{for } 1 < Q \leq 2)$$
$$C = 3F + vQ \qquad (\text{for } 2 < Q \leq 3)$$
$$C = nF + vQ \qquad (\text{for } n\text{-}1 < Q \leq n)\ .$$

This gives average cost functions of the form

$$AC = F/Q + v \qquad (\text{for } 0 < Q \leq 1)$$
$$AC = 2F/Q + v \qquad (\text{for } 1 < Q \leq 2)$$
$$AC = 3F/Q + v \qquad (\text{for } 2 < Q \leq 3)$$
$$AC = nF/Q + v \qquad (\text{for } n\text{-}1 < Q \leq n)\ .$$

And the marginal cost function is of the form

$$MC = dC/dQ = v\ .$$

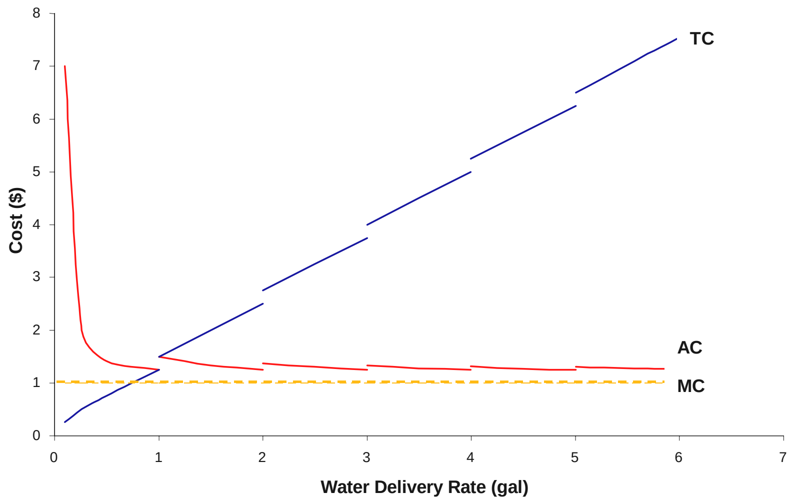

Exhibit 2.3. Cost function form for multiple water system.

The relationships between the total cost, average cost and marginal cost functions for either monitoring mode are illustrated by Exhibit 2.3. This exhibit has been constructed using individual total cost functions that are the same as the total cost function used to construct the single water system example illustrated by Exhibit 2.2. Consequently, up to Q = 1 the single and multiple water system cost functions are identical. Just beyond Q = 1 where the second of the multiple water systems begins production, the total cost function steps up by an amount equal to the additional fixed cost (.25) and increases linearly with slope equal to v, the unit variable cost (1.0).

This pattern is repeated with each water system replication. Initially, the average cost function decreases asymptotically toward the marginal cost, but stops at 1.25, just beyond which it increases with the first replication by an amount equal to the new fixed cost divided by the delivery rate plus the marginal cost. This pattern is repeated with each system replication resulting in a disjointed average cost function as illustrated. The "overall" average cost function tends asymptotically toward the individual water system average cost function minima which occur at the maximum delivery rate for each water system replication (1.25 in the example). The marginal cost is, as in the single system example, a constant value equal to the unit variable cost and is always below the average cost.

2.2 Parametric Simulation Cost-Effectiveness Model

2.2.1 Introduction and Model Summary

This section presents the spreadsheet-based simulation model after discussing its conceptual and mathematical formulation. The static deterministic parametric cost-estimating model is a spreadsheet-based decision-support tool that describes cost effectiveness of remote monitoring for rural water supply systems by performing a break-even analysis, as described in subsection 2.1.3, where the two operating alternatives are an existing water system with manual monitoring and the same water system with remote monitoring at the supervisory control level of automation.

Subsection 2.2.2 examines the basis of risk reduction attributable to remote monitoring followed by deriving the fundamental model equations. Subsections 2.2.3 through 2.2.5 document the spreadsheet-based model, including data and input requirements in Subsection 2.2.4, which includes a discussion of user-defined parameter estimation, a critical aspect of the model addressed in more detail by way of the example application in Part III. Model sensitivity is discussed in subsection 2.2.6, but numerical treatment of the subject is deferred until Section 3.3, where it is facilitated the example application.

The model is based upon fundamental assumptions regarding water system physical conditions that dictate the relationships among the production, loss and delivery of potable water illustrated schematically by Exhibit 2.4. Model formulation proceeds based upon these relationships and discussed in the preceding sections regarding physical and economic aspects of water systems. Linearity is a fundamental model assumption: all functional relationships in or contributing to the model are assumed to be linear.

The model performs a break-even analysis by simulating and graphing water system total operating costs as functions of water system delivery rate. Total operating cost is defined as the sum of fixed and variable costs over an annual operating period. At each operating rate, the remote-monitoring total cost differs from the manual-monitoring total cost by an amount equal to the increased fixed cost and decreased variable cost calculated by an adjusted variable cost parameter. The model calculates a new variable cost parameter Vr, the remote monitoring variable cost parameter by adjusting the manual monitoring variable cost parameter Vm to account for improved delivery efficiency attributable to decreased operating excursion duration. All loss-causing operating excursions are assumed to be stochastically independent and binary in nature, but of varying duration, as implied by historical records. The model range, specified by the independent variable, flow delivered, is established based upon historical production of the subject water system.

The manual- and remote-monitoring variable cost parameters (Vm and Vr) represent the unit variable cost of water delivered under either monitoring mode, and accordingly act against the simulated delivery rate to give respective variable costs. The manual-monitoring parameter is a constant calculated as a function of the delivery rate and variable cost inputs. The remote-monitoring parameter is a function of the manual-monitoring parameter and three remote-monitoring variable cost adjustment factors. These factors operate on Vm to obtain Vr based upon increased delivery efficiency attributable to remote monitoring.

The spreadsheet model consists of six spreadsheets and two break-even charts, including spreadsheet number 0 which contains explanatory notes and instructions. User interface is necessary for three types of input. The first consists of flow and cost data that are input to spreadsheet cells. The second consists of parameter values for interest rates and numbers of years from the present, necessary to calculate present-worth values, that are input at appropriate spreadsheet formula locations. The third consists of user-input parameter values that describe the extent of remote monitoring and monitoring frequencies associated with the remote monitoring variable cost parameter. These are input at appropriate cells of the remote monitoring variable cost parameter spreadsheet. Otherwise, the spreadsheet model executes automatically to generate the two break-even charts.

The break-even charts display the simulation by showing fixed and total operating costs for each monitoring mode as functions of flow delivered. Chart 1 displays the results for an operating range equal to twice the existing water system operating range to represent a single water system replication and chart 2 displays the results for only the existing water system operating range. These ranges were selected based upon information revealed during model development and testing. A range of twice the simulated maximum annual delivery rate was selected in accordance with two observations. First, based upon the linearity assumption and other factors, that a scale-up factor of two would preserve the functional relationships in the model. And second, that if any break-even prediction by the model would be relevant only within a singe capacity replication. Chart 2 shows only the existing operating range to provide a clearer view of the cost functions and the break-even point. Numerical output for the functions plotted on the break-even charts is provided on spreadsheet number 5.

2.2.2 Model Formulation

This subsection presents the mathematical formulation of the model after discussing the risk-reduction potential attributable to remote monitoring. The mathematical form of the model is obtained based upon the economic framework presented in Subsection 2.1.4 and assumptions regarding water supply system flow and loss characteristics.

As illustrated by Exhibit 2.4, water loss may occur at three generalized locations: at sections of the distribution system located either prior to or after major distribution system components or at the major components, which typically include storage tanks and pump stations. These losses are labeled QL_1, QL_2 and QL_3 in order of flow direction along the system from raw water intake through delivery to customers. As shown symbolically $QI = QP$ represents the assumption that there is no loss between the raw water intake and plant production. For purposes of model development there is no accuracy lost by combining the losses into a total loss $QL = QL_1 + QL_2 + QL_3$. This gives a fundamental model assumption: the volume delivered to customers is equal to the volume produced minus the loss volume ($QD = QP – QL$).

The source of delivery efficiency improvement or risk reduction can be understood by examining the relationship between the various water system flow components under manual versus remote monitoring. Distinguishing between manual and remote monitoring by the use of subscripts gives

$$QPm = QLm + QDm \quad \text{or} \quad QDm = QPm – QLm \qquad (1)$$

and

$$QPr = QLr + QDr \quad \text{or} \quad QDr = QPr – QLr \,. \qquad (2)$$

The difference between manual and remote monitoring with delivered water volume constant can be examined by setting QDm = QDr yielding

$$\text{QPm - QPr = QLm – QLr}$$

which means that the change in water production ($QPm - QPr$) due to remote monitoring will be equal to the change in water loss ($QLm - QLr$), which implies that the volume of water production with remote monitoring is equal to the volume of water production with manual monitoring minus the change in loss volume

$$QPr = QPm - (QLm - QLr) \,. \qquad (3)$$

In other words, for a given delivery volume, remote monitoring reduces production by an amount equal to the loss reduction. Consequently, the corresponding risk reduction is equal to the loss reduction against the unit variable cost.

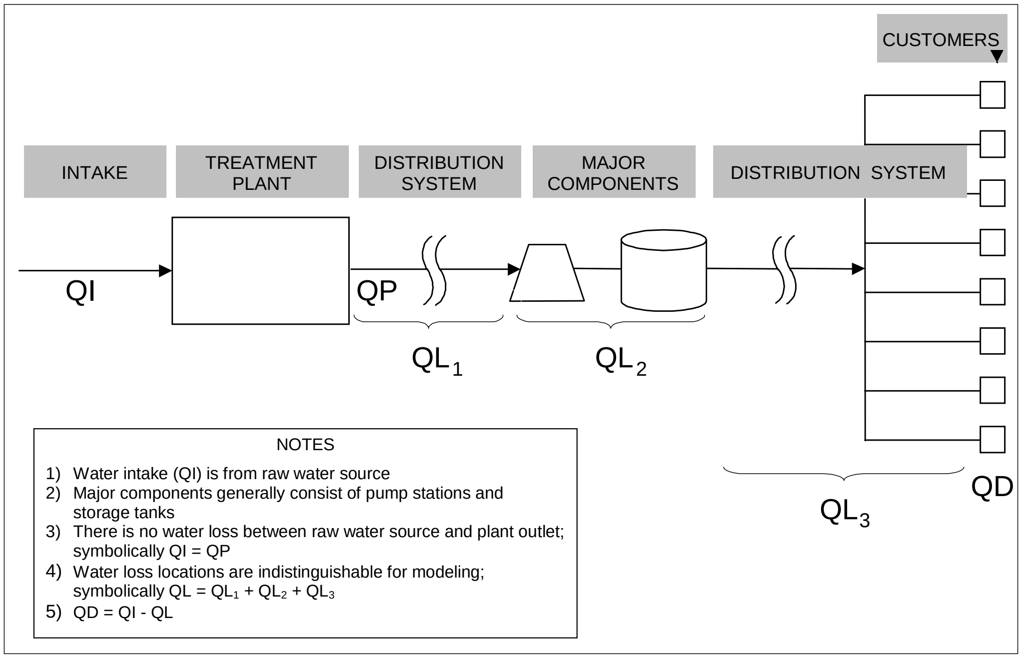

Exhibit 2.4. Simplified water supply system flow schematic showing general water loss locations.

The model simulates water system total operating cost *CT* as a function of potable water delivery rate *Q*, with total operating cost equal to the sum of fixed cost *CF* and variable cost *CV*.

$$CT(Q) = CF + CV \qquad \text{or} \qquad CT(Q) = CF + CV(Q)\,.$$

The linearity assumption allows specification of variable cost on a unit basis by a variable cost parameter *v* (cost/unit production) yielding the fundamental model equation

$$CT(Q) = CF + vQ \qquad \text{or} \qquad CT = CF + vQ\,. \tag{4}$$

This equation describes the relationship between total operating cost, fixed cost and variable cost as the product of delivery rate Q and a variable cost parameter v. This general relationship holds for the system with either manual or remote monitoring.

Defining specific equations to represent the relationships between total costs as functions of operating rate for the water system with manual monitoring and remote monitoring is accomplished by revising notation. By subscripting m for manual and r for remote, where all variables are otherwise defined as above, a set of total cost equations is obtained that can be utilized to use perform a break-even analysis:

$$CT_m = CF_m + v_m Q \tag{2.5}$$

$$CT_r = CF_r + v_r Q \; . \tag{2.6}$$

Defining the variables on an annual basis and production in gallons x 1000 gives the following units.

CT – total annual operating cost ($)

CF – annual fixed cost ($)

Q – production rate (1000 gal)

v – unit variable cost ($/1000 gal)

Total annual operating cost *CT* is calculated as the sum of the annual fixed cost *CF* and the annual variable cost vQ, where v is either v_m or v_r. Annual fixed cost generally represents an amortized annual value of the physical plant (equipment and inventory) and other indivisible costs, such as administrative salaries and contract services, depending upon accounting practices. Additional fixed costs associated with remote monitoring must be included where appropriate. Variable costs are those associated with inputs that vary with production rate such as chemicals and electricity.

This model can be configured to accommodate the possibility that break even may occur at delivery rates greater than existing water system capacity by simulating water system replications. This is accomplished by multiplying the single system fixed cost by the applicable replication factor to generate the replication fixed cost curve and applying the existing variable cost parameter to generate the variable cost portion of the total cost curve. The model so configured results in a step function for total cost, which for example, when simulating a doubling of system capacity or single replication yields the following set of equations, which are the basis of the spreadsheet model.

$$CT_m = CF_m + v_m Q \qquad \text{(for } 0 < Q \leq 1\text{)} \qquad (2.7)$$

$$CT_m = 2CF_m + v_m Q \qquad \text{(for } 1 < Q \leq 2\text{)} \qquad (2.8)$$

$$CT_r = CF_r + v_r Q \qquad \text{(for } 0 < Q \leq 1\text{)} \qquad (2.9)$$

$$CT_r = 2CF_r + v_r Q \qquad \text{(for } 1 < Q \leq 2\text{)} \qquad (2.10)$$

2.2.3 Spreadsheet Model

The spreadsheet model, without input, comprises approximately 115 kilobytes of Microsoft Excel consisting of one workbook containing six spreadsheets (numbers 0 through 5) and two break-even charts (charts 1 and 2). The spreadsheets either require user input/interface, perform calculations or both. Upon receiving all required input the model automatically performs the necessary calculations and generates the break-even charts. This subsection describes the spreadsheet model structure by explaining the flow of variable and parameter values among the spreadsheets and break-even charts. It also describes the general spreadsheet format.

Understanding the flow of variables and parameters among the spreadsheets is facilitated by a variable/parameter list and a flow schematic. Exhibit 2.5 includes, as a subset of the exhaustive model variable and parameter list, a summary list of variables and parameters used to construct the accompanying flow schematic shown as Exhibit 2.6. The schematic represents each spreadsheet and the break-even charts connected by dashed arrows indicating the model sequence from start to end. Variable/parameter flow is indicated by solid arrows to or from each spreadsheet with the variable or parameter symbol shown in an associated box. The schematic is drawn with parallel rows such that user inputs are shown entering spreadsheets from the row exteriors, and model-generated variable or parameter values are shown moving among the spreadsheets between the rows. The final numerical output, the simulated fixed and total costs for the water system with manual and remote monitoring, are shown flowing from spreadsheet number 5 to the break-even charts.

The principal model inputs are water system production (flow) data and actual operating or projected costs. Required flow data are monthly volumes produced (plant inflow) and delivered (billed) from appropriate records. Required cost data are of three types: annual fixed costs that represent the annual value of the physical plant and other indivisible costs for the water system with manual monitoring (existing system) from accounting records, estimated annual fixed costs of the remote monitoring system including design and installation from engineering or supplier estimates, and annual variable costs for the existing system from accounting records.

The model relies upon two years of data to represent the water system with manual monitoring and one year of data to represents the water system with remote monitoring. The system with remote monitoring is defined to exist in the "present" year and the system with manual monitoring is defined to exist in prior years "a" and "b." If insufficient data does not exist to provide all input for years a and b, the model can be run by adjusting existing data. For example, if only one year of historical data exists, these data can be repeated. It is important to note that error messages will be present in certain cells where spreadsheet calculations are performed prior to providing required input. Input requirements are addressed further in following subsections and in the discussion about the example application in Part III.

Two Excell functions are available to facilitate understanding the model structure. The first allows the user to locate variables and parameters that have been assigned names. This function allows the user to establish the location (spreadsheet cell) of a named variable or parameter by clicking in the formula box followed by clicking on the appropriate name, or conversely, to determine a name based upon a known location. The second allows the user to trace the dependents and predecessors of a variable or parameter by using the *auditing function*. The commands on the auditing toolbar allow the user to locate cells that provide data to a formula in an active cell or to find the cells that depend upon the value in an active cell. This function can be used to locate cells that provide data to a formula, that cause errors in a formula, that are referenced by a formula or that are located in another worksheet.

Variable or Parameter		Description
Summary	Model	
Qi	Qi	monthly flow produced, by individual system
Qd	Qd	monthly flow delivered, by individual system
	QIa	total flow produced – year a
	QIb	total flow produced – year b
	QDa	total flow delivered – year a
	QDb	total flow delivered – year b
	QLa	total flow loss - year a
	QLb	total flow loss - year b
	QI	annual average flow produced
QD	QD	annual average flow delivered
QL	QL	annual average flow loss
CFa	CFa	total fixed cost - year a
CFb	CFb	total fixed cost - year b
	CFWa	total present worth fixed cost - year a
	CFWb	total present worth fixed cost - year b
CFWm	CFWm	total (average) annual present worth fixed cost - manual monitoring mode
CFp	CFWp	additional annual (present worth) fixed cost for remote monitoring
CFWr	CFWr	total annual present worth fixed cost - remote monitoring mode
CVa	CVa	total variable cost - year a
CVb	CVb	total variable cost - year b
	CVWa	total present worth variable cost - year a
	CVWa	total present worth variable cost - year b
CVWm	CVWm	total (average) present worth variable cost - manual monitoring mode
Vm	Vm	manual monitoring mode variable cost parameter
Vr	Vr	remote monitoring mode variable cost parameter
	FL	remote monitoring mode loss factor
FX	FX	remote monitoring mode extent factor
	FT	remote monitoring mode frequency factor
Tm	Tm	manual monitoring frequency
Tr	Tr	remote monitoring frequency
	Qm	annual simulation flow delivered - manual monitoring mode
	Qr	annual simulation flow delivered - remote monitoring mode
i	i	annual interest rate (%)
FCm	FCm	simulated fixed cost – manual monitoring mode
FCr	FCr	simulated fixed cost – remote monitoring mode
TCm	TCm	simulated total cost – manual monitoring mode
TCr	TCr	simulated total cost – remote monitoring mode

Exhibit 2.5. Variables and parameters used in the model and as summarized in the spreadsheet model variable and parameter flow schematic.

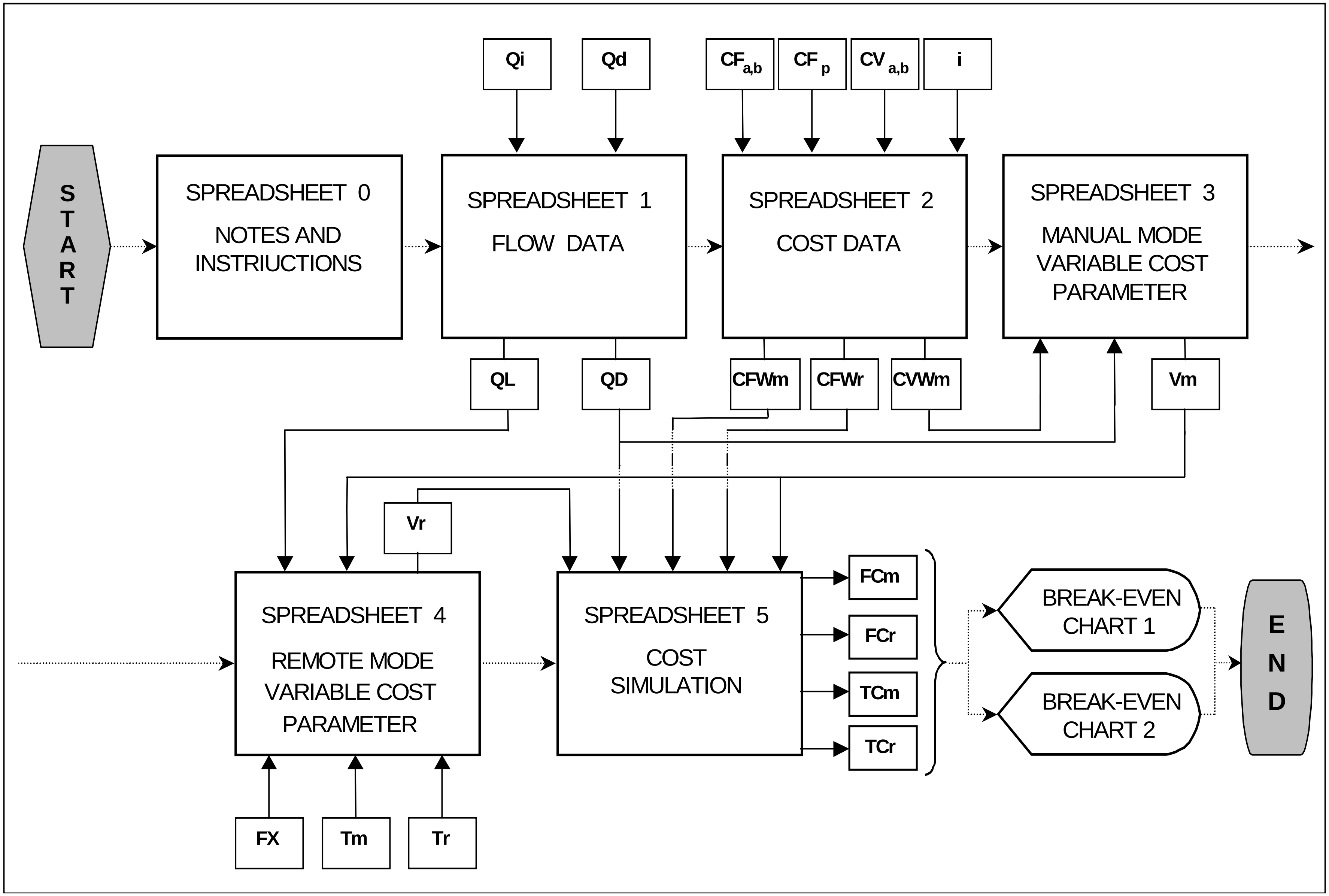

Exhibit 2.6. Spreadsheet model variable and parameter flow schematic.

The spreadsheets, presented after the model instructions in Subsection 2.2.5, are constructed and formatted for easy use. They are color coded and each contains comments to guide the user. Comments are named sequentially with two-character names: a numeral corresponding to the spreadsheet number and a letter assigned in order for the comments on each spreadsheet. Comments are indicated by a red tic mark in the upper right corner of the cell to which the comment applies, although tic marks do not appear on printed sheets. Comments are provided to explain each spreadsheet at the title, each cell or set of cells requiring user input/interface and each spreadsheet-calculated variable or parameter. Spreadsheet number 4 is an exception; it contains only one comment at the title, and all instructions or explanations are contained in a column of spreadsheet cells. For spreadsheet number 1, comments are repeated on the second page.

Spreadsheet color coding is as follows. Light blue is used for titles. Lime green is used to indicate notes or instructions, with associated headings of darker blue. Cells requiring numeric input are pale yellow, with associated headings of cream. Cells requiring alpha input are light green, with associated headings of darker green. Cells containing summary calculations such as sub-totals are brighter yellow. Cells containing calculated model variables or parameters are magenta. Cream is also used for certain other headings. Spreadsheet 5 is an exception: Lime green is used to show simulated flow delivered, pale yellow shows dependent variables or parameters not plotted on the break-even charts, and brighter yellow shows dependent variables plotted on the break-even charts.

2.2.4 Data/Input Requirements

The model requires input that has been grouped into four categories as shown in Exhibit 2.7. The nature of the data and their sources are generally described here and in the model instructions in Subsection 2.2.5, and further details about establishing input from raw data are provided by the example application in Part III.

Flow data consists of monthly quantities of potable water produced and delivered by individual water system for two years prior to the present year. The source of this data will typically be water supply system operating records. To prepare data for input, it should be placed in spreadsheet format showing monthly volumes produced, delivered, lost and any other pertinent categories. After data is in spreadsheet format it can be reworked to compensate for irregularities or model format incompatibilities to render it amenable to direct input to the model spreadsheet.

Model Input Descriptions and Sources	Associated Variable or Parameter
FLOW DATA	
monthly flow produced – system operating records	Qi
monthly flow delivered – system operating records	Qd
COST DATA	
annual fixed costs – year a – system accounting records	Cfa
annual fixed cost – year b – system accounting records	CFb
fixed costs for remote monitoring – engineering or vendor estimates	CFWp
variable costs – year a – system accounting records	Cva
variable costs – year b – system accounting records	CVb
MONITORING PARAMETERS	
remote mode extent factor – based upon anticipated (modeled) monitoring extent	FX
manual mode frequency – system operating records/operator recollection	Tm
remote mode frequency – based upon anticipated system (real-time ≈ 12/day)	Tr
PRESENT WORTH PARAMETERS	
annual interest rate(s) – common indices or actual rates	I

Exhibit 2.7. Simulation model input requirements.

Three types of cost data are required. Annual fixed costs and variable costs for the existing water system (manual monitoring) for two years prior to the present year must be selected based upon entries in accounting documents, such as annual financial reports. Fixed costs are those that do not vary with output and variable costs are those that do vary with output within the production period. For example, costs for indivisible inputs such as buildings and machinery, as well as costs such as salaried employee compensation will generally be considered fixed for an annual period. Variable costs are costs for inputs that vary with the level of production such as chemicals and electricity. Additional fixed costs for the remote monitoring system must be obtained from vendor or engineering estimates.

Costs representing the annual fixed cost of water system operation must be grouped into model input categories selected to assure that all costs are represented. Categories will typically include administrative and contractual expenses that can be selected from among operating expenses in financial reports or revenue statements. The fixed-cost category with the largest value will be the annual value of the *fixed plant*, the depreciated value of indivisible inputs such as land, buildings and equipment. The financial report entries selected to represent the annual value of the fixed plant will depend upon the accounting methods of the water system, particularly the method of handling depreciation and capital funding. As examples, in circumstances where depreciation is funded, these costs may be represented by *depreciation*, whereas in circumstances where depreciation is not funded, they may be represented by the sum of *principle payments on debt* and *insurance payments*. Another alternative is to base the value of annual fixed costs on cash flow where the annual fixed cost may be defined as the net *operating income* or *total operating revenues* minus *total operating expenses*.

Additional fixed costs associated with the remote monitoring system, for the present year, must be estimated based upon appropriate expertise, such as engineering or vendor estimates. Equipment, inventory, design and installation costs must be included. Costs for replacement components during the expected life of the monitoring system must also be included.

Variable costs for the existing water system for the two prior years must be selected based upon entries in accounting documents, such as annual financial reports. This will typically be done by selecting cost categories from the applicable revenue statements. Variable costs such as those for chemicals and electricity may appear in revenue statements as annual costs specifically for these items. Annual variable cost of water system operation may be grouped into model input categories such as water treatment, operation and maintenance, and miscellaneous and unclassified.

The model contains <u>five user-input parameters</u>: three remote-monitoring parameter factors and the annual interest rates used in present-worth calculations for annual fixed and variable costs.

The remote-monitoring extent factor defines the extent to which remote monitoring will be implemented, based upon the size and nature of the water system and mechanical components designated for monitoring. The manual- and remote-monitoring frequencies are factors that specify monitoring frequencies with either type of monitoring. Selection of the values for these factors is discussed in the model instructions in Subsection 2.2.5 and as part of the discussion of model sensitivity in Subsection 2.2.6. The example application further addresses selection of parameter values in Part III.

The remote-monitoring extent factor FX describes the extent of remote monitoring as a fraction of the maximum potential water loss reduction. It is estimated based upon user-interpretation of water system physical conditions, monitoring system configuration and information about historical loss events. The physical nature of the water and monitoring systems can be determined from engineering or other design documents, while sources of information about historical water losses may include operational records and operator recollection.

The remote-monitoring frequency factor FT is a model-calculated parameter that is a function of the user-input remote- and manual-monitoring frequencies Tm and Tr. The manual-monitoring frequency Tm is the average frequency of system component monitoring with manual monitoring, and the remote-monitoring frequency Tr is the average frequency of system component monitoring with remote monitoring. Tr is generally estimated at twelve (12) per day, the value used to represent real-time monitoring with allowance for operator down time or other lag-causing events.

The cost spreadsheet converts prior year values to present-worth values based upon default or user-defined average annual interest rates. These may be estimated utilizing water system specific information or commonly available indices. For the example application the interest rate associated with fixed costs was calculated as the dollar-weighted average of outstanding bond interest rates, and the interest rate associated with variable costs was calculated based upon the U.S. Bureau of Labor Statistics consumer price indices.

2.2.5 Instructions

This subsection gives the model instructions referenced to the spreadsheets and the two break-even charts. The spreadsheets, with all comments visible, are presented at the end of this subsection as exhibits 2.8 through 2.13. The break-even charts are not presented until Part III with results of the example application.

Prior to running the model it should first be saved without modification or input by saving the Excel file in an appropriate location and making a copy of the model by saving the Excel file renamed in an appropriate location. After saving these files the user should use only the renamed copy. To run the model all notes and instructions should be read first, and the thesis model description of Section 2.2 and the example application of Section 3.2 should also be read. Then, during model use, reference can be made to the comments on each spreadsheet. It should also be noted that Subsection 1.2.4 provides additional information that may be useful for selecting and categorizing cost inputs.

The values of five parameters must be established prior to running the model. The nature and methods of estimating these user-input parameters are discussed in the instructions for the pertinent spreadsheets. The effect of these parameter values on the model results is discussed under model sensitivity in Subsection 2.2.6 and further explained by the sensitivity analysis of the example application in Part III. The user-input parameters may be estimated in more than one way depending upon data availability.

Three of the user-input parameters are used in spreadsheet number 4 which calculates the remote-monitoring variable cost parameter. The remote-monitoring extent factor FX describes the extent of remote monitoring planned for the water system as a fraction of the maximum potential loss reduction. Typically, a water system will incorporate remote monitoring at one of two general extents: either at all major mechanical components such as tanks, pump stations, etc. or at strategic distribution system locations in addition to major mechanical components. Parameter estimation must be facilitated by information about system configuration and operating excursion history. Sources of this information about the remote-monitoring extent factor may include water system plans, operating records and operator knowledge.

The remote-monitoring frequency factor FT is a model-calculated parameter that describes system water loss reduction attributable to increased monitoring frequency. It is calculated from the manual- and remote-monitoring frequencies Tm and Tr input by the user. The manual-monitoring frequency Tm is the average frequency of system component monitoring with manual monitoring, and the remote-monitoring frequency Tr is the average frequency of system component monitoring with remote monitoring. The value of Tr will generally be on the order of 12, which represents real-time data transmittal limited by operator interaction at the level of every two hours. Tm must be determined based upon an appropriate method. This may be done by simply estimating a weighted-average monitoring frequency from operations records or operator recollection.

The remaining two user-input parameters are used on spreadsheet number 2 to calculate present-worth values for annual fixed costs and annual variable costs. The user must interface at the applicable cells to specify annual interest rate(s) and numbers of years from present year by revising default values at the spreadsheet formulas. These values must be estimated based upon either actual rates paid by the system for capital or from standard indices such as a Consumer Price Index.

After the user-input parameter values have been determined the model can be run by following the instructions in sequence.

Open Spreadsheet Number 1 - Flow Data. This spreadsheet, consisting of two pages, sums two years of monthly flow data (produced and delivered) input by individual water system and calculates system average annual quantities produced - QI, delivered - QD, and lost - QL.

One set of input is required. Individual water system names should be input at column A. Corresponding monthly flow volumes must be input at columns B through AW: volume produced - Qi and volume delivered - Qd. Units are thousands of gallons (e.g., 100,000 gallons is input as 100). Two years of data must be entered (years a and b). If two years of data are not available, the user must adjust the available data. For example, to adjust for only one year of data, the user may copy the data for the second year.

Open Spreadsheet Number 2 - Cost Data. This spreadsheet sums two years manual monitoring fixed cost data and present year remote monitoring fixed cost data input by cost category and calculates the respective present worth values (CFWm and CFWp); it then calculates the remote monitoring fixed cost as the sum of the annual present worth fixed costs (CFWr = CFWm + CFWp). It sums two years variable cost data input by cost category to calculate the annual manual monitoring variable cost present worth (CVWm). Three sets of input/interface are required:

(1) Manual-monitoring annual fixed cost category names should be input at column A. Corresponding annual values by category for years prior to the present year (a and b) must be input at columns B and C. Units are dollars without decimals. The user must interface at cells B17 and C17 to provide parameter values for calculation of present-worth sum of fixed costs for years a and b - CFWa and CFWb. The annual interest rate(s) and numbers of years from present year must be specified by revising default values. To do this the user must go to the cell formula and enter interest rate in first field (default is 5%) and enter number of years from present in second field (defaults are 2 and 1 for years a and b). The % symbol must not be omitted and the other fields must not be revised. The user should be alert to observe that the calculated values of CFWa and CFWb should be approximately equal; if they are not, the input should be reviewed.

(2) Remote-monitoring fixed cost category names should be input at column A. Corresponding estimated total values (present year) and estimated component lives by category must be input at columns B and C. Units are dollars without decimals and years.

(3) Manual-monitoring variable cost category names should be input at column A. Corresponding annual values by category for years prior to present (a and b) must be input at columns B and C. Units are dollars without decimals. The user must interface at cells B45 and C45 for calculation of present-worth sum of variable costs - CVWa and CVWb. The annual interest rate(s) and number of years from present year must be specified by revising default values. To do this the user must go to the cell formula and enter interest rate in first field (default is 3%) and enter number of years from present in second field (defaults are 2 and 1 for years a and b). The % symbol must not be omitted and the other fields must not be revised.

<u>Open Spreadsheet Number 3 – Manual-Mode Variable Cost Parameter (Vm)</u>. This spreadsheet automatically calculates the manual-monitoring variable cost parameter - Vm as the average of the year a and b annual unit variable costs. It obtains annual flow data (volumes delivered - QDa and QDb) from spreadsheet number 1 and variable cost data (present-worth variable costs - CVWa and CVWb) from spreadsheet number 2.

<u>Open Spreadsheet Number 4 – Remote-Mode Variable Cost Parameter (Vr)</u>. This spreadsheet calculates the remote-monitoring variable cost parameter - Vr as a function of the manual-monitoring variable cost parameter - Vm and three remote-monitoring variable cost adjustment factors that account for improved water system delivery efficiency (i.e., decreased loss – QL) attributable to remote monitoring. Three user inputs are required:

(1) FX = Remote-Mode Extent Factor: This factor describes the extent of remote monitoring planned for the water supply system as a fraction of the maximum potential loss reduction. Typically, a system will incorporate remote monitoring at one of two general extents: either all major mechanical components such as tanks, pump stations, etc. will be monitored remotely or all major mechanical components and strategic distribution conduit locations will be monitored remotely. For remote monitoring of major mechanical components only, a factor value range is 0.20 to 0.40, with 0.30 typical; for major components and conduits a factor value range is 0.45 to 0.85, with 0.65 typical. The user must estimate these values based upon water supply and monitoring system configurations and historical loss information. Input must be in the form 0.XX - two digits to the right of a decimal.

(2) Tm = Manual-Mode Monitoring Frequency: The user must input the average frequency of water system component monitoring with manual monitoring. Units are number of monitoring events

(per unit time), and must be the same units as remote-mode monitoring frequency, below. User input must consist of the number only, such as 1 representing one monitoring event per day.

(3) Tr = Remote-Mode Monitoring Frequency: The user must input the average frequency of water system component monitoring with remote monitoring. Units are number of monitoring events (per unit time), and must be the same units as manual-mode monitoring frequency, above. User input must consist of the number only, such as 12 representing twelve monitoring events per day. 12 is recommended as the maximum value - used to represent real-time monitoring with allowance for operator absence or other lag-causing events.

Open Spreadsheet Number 5 - Cost Simulation. This spreadsheet automatically calculates fixed costs, variable costs and total costs as functions of simulated water system flow - Q (based upon the average existing water system flow delivered - QD) for the water system with manual and remote monitoring. Fixed costs and total costs are then plotted to create the break-even charts.

Open Break-Even Charts. The break-even charts show the simulated fixed and total costs as functions of simulated water system flow. Chart 1 ranges from zero to two 2Q (two times the maximum simulated flow), and Chart 2 ranges from zero to Q to give a more detailed view of the range within which break-even is likely to occur. The point(s) at which the total costs, CTm and CTr, intersect is the break-even point(s). This completes the model run. There is no user input or interface required, but chart titles may be changed by clicking on the titles and typing over the existing titles.

Exhibit 2.8. Spreadsheet number 0: notes and instructions.

Exhibit 2.9. Spreadsheet number 1: flow data.

Exhibit 2.10. Spreadsheet number 2: cost data.

Exhibit 2.11. Spreadsheet number 3: manual mode variable cost parameter.

Exhibit 2.12. Spreadsheet number 4: remote mode variable cost parameter.

Exhibit 2.13. Spreadsheet number 5: cost simulation.

2.2.6 Sensitivity

The subsection provides a general discussion about model sensitivity by discussing the key model parameters. A numerical sensitivity analysis is presented in Section 3.3 with results of the example application.

Model parameter values are either calculated automatically by the model or input by the user. The primary model parameter: the manual-monitoring variable cost parameter Vm is automatically calculated by the model.

Spreadsheet number 3 calculates the manual-monitoring variable cost parameter based upon existing water supply system flow and variable cost inputs. Spreadsheet number 4 then calculates Vr as a function of Vm and three remote-monitoring variable cost adjustment factors: FL, FX and FT. Vr is determined by adjusting Vm to account for improved delivery efficiency attributable to remote monitoring in accordance with

$$Vr = Vm\ (Qm/Qr) \qquad (2.11)$$

where

$$Qr = Qm + (FL*FX*FT) \qquad (2.12)$$

and

$$FT = 1 - (Tm/Tr)\ . \qquad (2.13)$$

Qr is the simulated annual volume of water delivered with remote monitoring and Qm is the volume delivered with manual monitoring, which is equal to the average volume delivered for the water system with manual monitoring QD based upon model input. As shown, Qr is calculated by increasing Qm by an amount equal to the multiplicative result of the three remote-monitoring variable cost adjustment factors.

The remote-monitoring loss factor FL is a parameter that describes the maximum potential water loss reduction or delivery efficiency improvement attributable to remote monitoring. It is equal to the total average water loss for the water system with manual monitoring QL from model input and is automatically calculated by the model.

The remote-monitoring extent factor FX is a user-specified parameter that describes the extent of remote monitoring planned for the water system as a fraction of the maximum potential loss reduction. Typically, a water system will incorporate remote monitoring at one of two general extents: either all major mechanical components such as tanks and pump stations, or strategic distribution conduit locations in addition to all major mechanical components. For remote monitoring at major mechanical components a factor value range is 0.20 to 0.40, with 0.30 typical; for strategic distribution conduit locations in addition to all major components a factor value range is 0.45 to 0.85, with 0.65 typical.

The remote-monitoring frequency factor FT is a model-calculated parameter that describes increased water system delivery efficiency attributable to increased monitoring frequency. It is calculated from the remote- and manual-monitoring frequencies Tm and Tr input by the user. The manual-monitoring frequency Tm is the average frequency of water system monitoring with manual monitoring, and the remote-monitoring frequency Tr is the average frequency of water system monitoring with remote monitoring.

The user must also input the value of the annual interest rate(s) used to calculate present-worth values for annual fixed costs and annual variable costs that appear on spreadsheet number 2. This is done by revising default values at the cells containing spreadsheet formulas.

Model sensitivity can be examined by observing how simulated total operating costs and the associated break-even point(s) are dependent upon the relative values of Vm and Vr, as they change in response to changes in user-input parameter values. This can be observed by artificially varying the value of FX, which is the user-input parameter judged to be most difficult to determine and therefore likely to be least accurate. The value of FX may be varied within the range of a monitoring extent, e.g., between 0.20 to 0.40 for monitoring at major mechanical components only, without revising other inputs. However, in cases when FX is changed such that it moves out the applicable range, such as when increasing monitoring to include strategic distribution conduit locations in addition to all major mechanical components, the additional fixed costs for remote monitoring must also be increased accordingly.

2.2.7 Discussion

A spreadsheet-based parametric simulation model was developed to enable users to analyze cost effectiveness of remote monitoring for rural water supply systems. The model serves as a decision-support tool useful to water system management personnel and researchers by performing a graphic break-even analysis comparing water system operating costs with manual and remote monitoring.

The model was developed by transforming fundamental concepts regarding water system operation and remote monitoring technology into the mathematical and spreadsheet model forms. The model operates on water system flow and cost inputs and user-input parameter values to calculate water system total operating costs as functions of potable water delivery, which are plotted to illustrate the break-even point(s).

The model requires care in selection and adjustment of appropriate flow and cost data, and in estimating five user-input parameter values. All data are expected to be readily available from water system operating records, accounting documents, or for remote monitoring system fixed costs, engineering or vendor estimates. Information for estimating some user-input parameters may vary with the water system under evaluation, so users must have fundamental knowledge about water system operation and remote monitoring to estimate these values. When the user is cognizant of these requirements and is able to provide reasonably accurate data and parameter estimations, the model is a valuable planning and research tool. However, it is not intended for budgeting or other uses that require a higher degree of accuracy.

The model is sensitive to five user-input parameters: the remote-monitoring extent factor FX, the manual-monitoring frequency Tm, the remote-monitoring frequency Tr, and two interest rate parameters used in present-worth adjustments. Tm, Tr and the interest rates can generally be estimated easily with a reasonably high degree of accuracy. Estimating FX accurately will generally entail more user effort, but should be determinable with reasonable accuracy when the user possesses adequate background information or consults adequate references.

The model is fully functional in its current state and has been designed to serve as the foundation of an enhanced simulation model or a more comprehensive MIS that would be useful to water system managers. An enhanced simulation model could feature automated parameter estimation to replace the user inputs required in the current model. A comprehensive MIS would serve water system management personnel by providing expanded data management capabilities. These would include database/spreadsheet features designed to enable operating-cost allocation and GIS features designed to aid remote monitoring system design and optimization.

Model accuracy was evaluated by comparing simulated total operating costs to actual water system operating costs based upon Tazewell County (Virginia) Public Service Authority billing rates. This comparison indicated that the parametric simulation cost effectiveness model is extremely accurate at estimating total operating costs as the simulated total unit operating cost of $6.48/1000 gallon compared favorably to actual billing rates of $5.24/1000 gallon or $8.00/1000 gallon depending upon usage. (Town of Tazewell, 2002)

Part III – Example Application: The Tazewell County, Virginia Water Supply System

3.1 Tazewell County, Virginia Water Supply System

3.1.1 Historical and Geographic Setting

When in 1750 Dr. Thomas Walker visited the area that is now Tazewell County, Virginia he remarked in his diary about the lush grass, plentiful game and large quantities of coal. Fifty years or more passed before the great wealth of coal at Pocahontas was exploited and the era of new towns and the railroad began. Tazewell became a Virginia county on 19 December 1799 after the first permanent white settler, Thomas Witten arrived to stay about 1770. Miners, many from eastern Europe, often remained in the area and today descendants of these first settlers still live on the land (often the original land grants). With the coming of the railroad in the late 1880's, the county advanced in exporting agricultural products and coal. (Town of Tazewell, 2002)

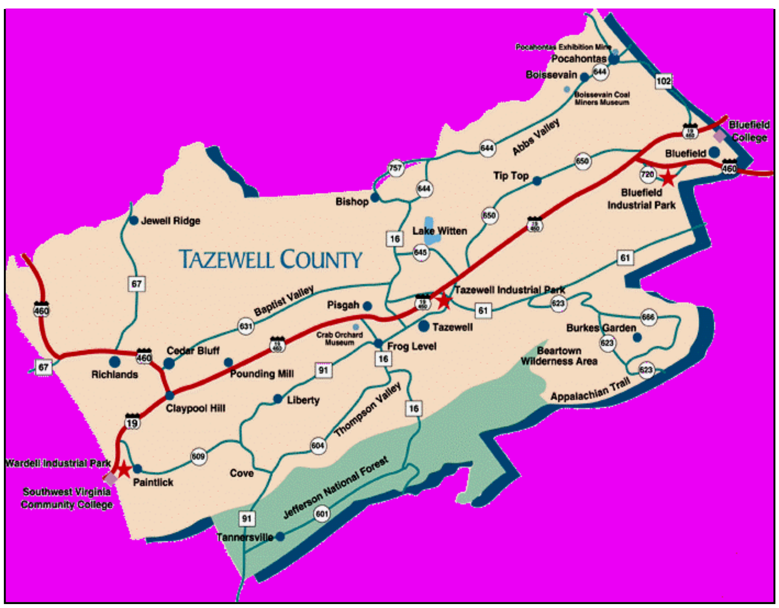

Exhibit 3.1. Map of Tazewell County, Virginia showing highways, towns and significant features.

Tazewell County, depicted on Exhibit 3.1, encompasses 522 square miles in southwestern Virginia within the valley and ridge province of the Appalachian Highlands between the Appalachian Mountains on the southeast and the Cumberland Plateau and the Allegheny Mountains on the northwest. The Town of Tazewell, which serves as the county seat, is located in the geographical center of the county about 22 miles southwest of Bluefield, West Virginia, 79 miles northeast of Bristol, Virginia and 85 miles west of Roanoke, Virginia. (Town of Tazewell, 2002)

The elevation of the Tazewell area ranges from 1,900 feet on the valley floor to 4,700 feet on the mountain ridges with an average elevation of about 2,380 feet. Surface features range from sloping to hilly and steep, with comparatively small areas of smooth and gentle rolling countryside. Locations of major rivers and streams within the county as shown on Exhibit 3.2 indicate geographic relief. The climate is characterized by relatively warm summers and mild winters, with a mean annual temperature of 49F. The average summer temperature is 61F, with an annual high of 92F. The average winter temperature is 39F with an annual low of 24F. Annual rainfall averages about 42 inches, and the average annual snowfall is about 39 inches with a range of 15 to 75 inches. (Town of Tazewell, 2002)

There are four incorporated towns in the county in addition to Tazewell, each with unique and special traits. Richlands, in the western part of the county, still reflects the energy which once earned it the name of "Pittsburgh of the South"; Cedar Bluff, east of Richlands, retains an historical quiet charm; Bluefield, in the eastern part of the county near its twin city of Bluefield, West Virginia is Virginia’s “tallest town” with elevation up to 3,800 feet; Pocahontas, to the north of Bluefield is a living museum of coal mining. (Town of Tazewell, 2002)

According to year 2000 U.S. Census Bureau information there are 18,277 households in the county, and the Tazewell County webpage lists a 2002 population of 44,598 distributed as follows: Bluefield - 5,078, Cedar Bluff - 1,300, Pocahontas - 450, Richlands - 4,150, Tazewell - 4,676, and county - 28,944. With routes 19 and 460 passing through, businesses and industry are expanding, along with an increasing number of tourists who enjoy camping, fishing and hiking the Appalachian Trail. Easy access to markets is made possible by rail service and proximity to major highways I-77, I-81 and Rt. 19/460. Additionally, the Tazewell County airport, completed in 1992, provides local air service. (Tazewell County, 2002)

3.1.2 Water System Physical Components

The physical subsystem of the Tazewell County water supply system consists of nine individual water systems that produced a total of approximately 310,681,000 gallons in 1998, or 309,800,000 gallons excluding the Town of Tazewell individual water system. The relevance of this exclusion is addressed in the following paragraph. Locations of major water system mechanical components consisting of storage tanks, booster stations and other components, are shown on Exhibit 3.2 and listed in Exhibit 3.3. Monthly volumes of potable water produced and delivered to customers by individual water system and totals for the Tazewell County water system are shown in Exhibit 3.4. (TCPSA, 2001)

With two exceptions, the Falls Mills and Tazewell systems, potable water is produced at individual water system plants and distributed to customers within respective jurisdictions. However, the Falls Mills water system does not produce water, but rather purchases potable water from the Pocahontas, West Virginia water system and distributes it to customers. For the Tazewell water system flow is complicated by the fact that the it does not include storage tanks. Consequently, the Tazewell water system sells water to and repurchases water from the Town of Tazewell water system which is not an individual system of the Tazewell County water system. (Dowdy, 2002)

Implication of the Falls Mills water system flow idiosyncrasy is the difficulty of assigning a fixed cost to represent the corresponding fixed plant value (reference subsections 2.2.4 and 3.2.2). Therefore, the total cost of operating the Falls Mills system is represented by the Tazewell County Public Service Authority financial statement entry *purchased water*, which becomes part of the model variable cost category "water treatment" (reference exhibits 3.8, 3.10 and 3.13). Implication for the Tazewell water system flow idiosyncrasy is that it is essentially impossible to determine water loss volumes for the system. Therefore, as the Tazewell water system accounts for much less than one percent of the total Tazewell County water system production, both production and costs attributable to this individual system were excluded.

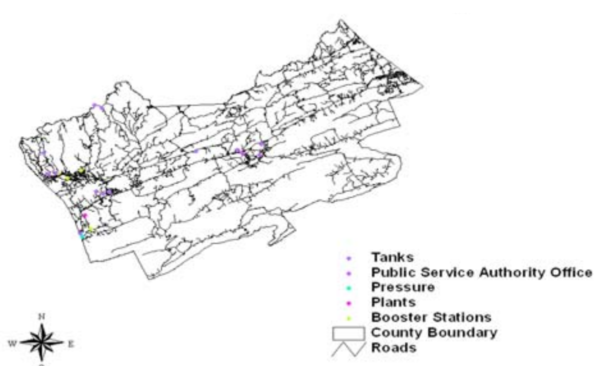

Exhibit 3.2. Location of Tazewell County water supply system major mechanical components.

System	Volume Produced	Tanks	Booster Stations	Other Components
Claypool Hill	139,352,000	5	2	-
Raven/Doran	109,619,000	1	-	-
Boissevain	14,580,000	1	1	-
Amonate	3,452,000	1	-	-
Jewel Ridge	6,276,000	1	-	-
Bishop	6,077,000	1	-	-
Falls Mills	21,594,000	1	-	-
Bluefield	8,850,000	1	1	-
Tazewell	881,800	NA	NA	NA
TOTALS	310,680,800	12	4	-

Exhibit 3.3. Components of the individual water systems comprising the Tazewell County water supply system and 1998 production volumes.

3.1.3 Water System Operating History

Two relevant aspects of water supply system operating history become intrinsically reflected by the model upon completion data and user-input parameter input. Water system operating excursion (water loss quantity) history indicates the maximum potential risk reduction achievable with remote monitoring and temporal production variations yield information about water system response time.

Total annual water loss is calculated by the model at the flow data spreadsheet based upon inputs for potable water produced and delivered. The monthly volumes input by individual water system are consolidated and averaged by the model generating the system-wide average annual historical loss volume, which later becomes the remote mode loss factor used to calculate the remote mode variable cost parameter that defines the maximum potential risk reduction. Temporal production variations reveal water system response time that is reflected in the model by the remote mode frequency factor. This factor, calculated from user-input remote and manual monitoring frequencies, describes water system loss reduction attributable to increased monitoring frequency of remote monitoring.

Tazewell County water system operating information is provided by the water loss history for calendar year 1998 as summarized in Exhibit 3.4, which shows volumes of water produced and percentages delivered and lost by individual water system. Total system loss for 1998 was 32 percent of approximately 309,800,000 gallons produced or 99,136,000 gallons. The variable cost of this loss represents the potential maximum annual risk reduction attributable to delivery efficiency improvement from remote monitoring based upon 1998 system operating characteristics. Applying the unit variable cost of water ($3.43/1000gal.) calculated by the model as explained in the results for the example application gives an associated present value of $340,036. (TCPSA, 2001)

Water production varies in response to demand as determined by storage drawdown that includes water loss. Graphic analysis of individual water system operating data as daily production versus time revealed that water demand showed seasonal, monthly and daily variations of which daily were substantially the most pronounced. This indicates that the response to water losses may occur within about one day. The Claypool Hill system, which significantly, is the largest individual water system, is typical in this regard as indicated by the July 2000 operating data shown on Exhibit 3.5.

System	Volume Produced	% Sold	% Loss
Claypool Hill	139,352,000	57	43
Raven/Doran	109,619,000	73	27
Boissevain	14,580,000	79	21
Amonate	3,452,000	112	-12
Jewel Ridge	6,276,000	83	17
Bishop	6,077,000	102	-2
Falls Mills	21,594,000	75	25
Bluefield	8,850,000	93	7
TOTALS	309,800,000	68	32

Exhibit 3.4. 1998 water loss summary for the Tazewell County water supply system.

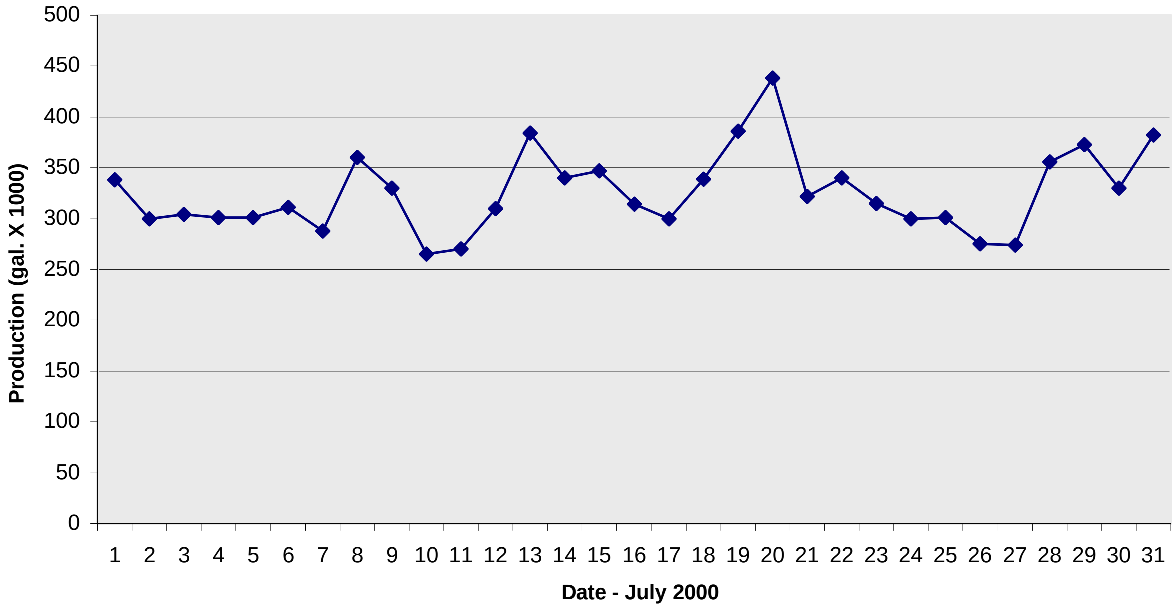

Exhibit 3.5. Daily production for the Claypool Hill individual system – July 2000.

3.2 Model Description

3.2.1 Introduction

The model was run to perform a break-even analysis to compare manual and remote monitoring for the year 1998 Tazewell County water supply system, with the exclusion of the Town of Tazewell individual water system because of the flow idiosyncrasy explained in Section 3.1. The extent of remote monitoring modeled for the example application is major mechanical components only, which limits the range of the user-input parameter FX that describes the extent of monitoring, as explained in Section 2.2. Major mechanical components specified for the model run consists of twelve tank and four booster pump monitoring locations listed in Exhibit 3.3.

3.2.2 Data and Input

Four principal sets of input derived from data obtained from two sources from the Tazewell County Public Service Authority: operating data for the county water supply system for the period 1998 through 2000 and the 1998 Tazewell County Public Service Authority Financial Report. These data were reworked as described below to generate the model inputs. All inputs are based upon an annual operating period. (Hicok and Fern, 1998) (TCPSA, 2000)

Flow data consisted of spreadsheets containing monthly volumes of water produced, sold and lost by individual water system. In certain cases, the spreadsheets also contained entries for volumes "adjusted." Data analysis revealed that volume delivered, a required input, is equal to volume sold plus volume adjusted. Because the flow data were incomplete and the spreadsheet format was incompatible with the model spreadsheets it was necessary to rework the data content and format.

Exhibit 3.6 shows the content and format of the flow data spreadsheets as received (clear) and as reworked (shaded) for the Claypool Hill system. Typical of the data received, certain entries for percentage lost and sold were not provided, which meant that these percentages and the associated volumes could not be calculated without reworking the data. Flow data were reworked by estimating the missing data, results of which are exemplified on Exhibit 3.6, and by reformatting the spreadsheets for model compatibility as shown by Exhibit 3.7.

Missing data were estimated by a two-component linear interpolation function based upon the observed relationships of loss data for the entire year 1999 and the latter part of 1998. The 1999 data provided a monthly variation component, and the 1998 data provided a magnitude component. The completed data sets were then used to calculate monthly volumes produced and delivered that then became model input. When data sets for all individual water systems were complete, the adjusted flows were consolidated into the transposed format shown as Exhibit 3.7 for input at spreadsheet number 1.

Fixed and variable costs for water system operation with manual monitoring were extracted from two parts of the 1998 Tazewell County Public Service Authority financial report. Operating expenses from the revenue statement summarized as Exhibit 3.8 served as the source of all fixed or variable costs except fixed costs representing the category fixed plant. The annual value of fixed plant was defined as the sum of insurance and principal payments on debt (loans and bonds) from the financial report cash flow statement, as discussed further below.

In general, two types of data reworking were necessary after cost selection and categorization. Fixed costs and variable costs were revised to compensate for the fact that they include the portion of costs associated with operation of the Public Service Authority's sewerage treatment plant. This was accomplished by attributing only fifty percent of each common-cost entry to the water system for applicable cost categories, as noted on the cost tables of exhibits 3.9 and 3.10. In addition to this data revision, variable costs were reworked to account for exclusion of the Town of Tazewell individual water system as explained in Section 3.1.

	PRODUCT	PROD/1000	ADJUST	SOLD	LOSS	LOSS/1000	%SOLD	%LOSS	99 LOSS
Jan	11,101,000	11,101	-	6,338,406	4,762,594	4,763	57	43	52
Feb	11,325,000	11,325	-	6,893,447	4,431,553	4,432	61	39	48
Mar	11,332,000	11,332	-	4,766,021	6,565,979	6,566	42	58	67
Apr	11,249,000	11,249	-	6,266,835	4,982,165	4,982	56	44	53
May	11,754,000	11,754	-	6,174,827	5,579,173	5,579	53	47	56
June	11,514,000	11,514	-	7,060,408	4,453,592	4,454	61	39	48
July	12,044,000	12,044	164,876	6,326,950	5,552,174	5,552	54	46	26
Aug	12,184,000	12,184	285,635	9,170,300	2,728,065	2,728	78	22	49
Sept	11,557,000	11,557	452,590	6,073,100	5,031,310	5,031	56	44	39
Oct	12,263,000	12,263	137,818	6,580,800	5,544,382	5,544	55	45	42
Nov	11,686,000	11,686	208,329	7,178,700	4,298,971	4,299	63	37	52
Dec	11,343,000	11,343	654,505	5,344,700	5,343,795	5,344	53	47	56
TOT	139,352,000	139,352	1,903,753	78,174,494	59,273,752	59,274	60	40	49

Exhibit 3.6. Raw and adjusted production and loss data for the Claypool Hill water system - 1998.

Costs representing the annual fixed cost of water system operation were grouped into two model input categories: fixed plant and administrative and contractual expenses, as listed in Exhibit 3.9. Administrative and contractual expenses were selected from among operating expenses in the 1998 financial report revenue statement. These were then adjusted, where necessary, to account for inclusion of the inextricable expense of sewerage plant operation.

Selection of financial report entries to represent the annual cost of the water system fixed plant required conducting a review of accounting methods applicable to public entities and determining how to best represent this category for the Tazewell County Public Service Authority based upon its accounting practices. Primarily because the authority does not fund depreciation, it was decided to define fixed plant as the sum of insurance payments and principal payments on loans and bonds indicated on financial report cash flow statements. Again, as shown on Exhibit 3.9, these entries were also adjusted to account for inclusion of the inextricable expense of sewerage plant operation. (Spencer, 2001)

Costs representing the annual variable cost of water system operation were grouped into three model input categories – water treatment, operation and maintenance, and miscellaneous and unclassified, as listed in Exhibit 3.10. All of these costs were obtained from the financial report revenue statement. Costs were adjusted where necessary to account for inclusion of the inextricable expense of sewerage plant operation and to reflect exclusion of the Town of Tazewell individual water system. After data reworking, the category totals for fixed costs shown in Exhibit 3.9 and variable costs shown in Exhibit 3.10 were input to the model at spreadsheet number 2.

Additional fixed costs associated with implementing remote monitoring were based upon a categorized estimate in accordance with the model assumption that the extent of remote monitoring would include all major mechanical components at the supervisory control level of automation.

This estimate was developed based upon information obtained during the research phase of the Project with assistance of an experienced remote monitoring system designer and equipment supplier. As shown on Exhibit 3.11, total costs were estimated for six categories – tank units, booster station units, base computer and related, design, installation and spare inventory/upgrades. As shown, twelve tank units and four booster station units were included, as well as design and installation fees at fifty percent each. The estimated total costs and estimated useful system life of seven years were input to the model at spreadsheet number 2. (Melton, 2002)

1998 FLOW DATA TRANSPOSED (1000 gallon)												
PRODUCE	J	F	M	A	M	J	J	A	S	O	N	D
CPH	11101	11325	11332	11249	11754	11514	12044	12184	11557	12263	11686	11343
RD	9263	8810	9450	9232	10536	9748	10140	11010	7869	7981	7823	7757
Bois	1422	1228	1225	1447	1224	1235	1422	1059	1070	1150	1020	1078
Amon	270	338	333	284	267	304	345	294	270	268	235	246
JR	737	465	579	296	253	557	855	416	449	581	528	559
Bishop	479	431	466	479	492	532	560	603	500	508	528	501
Falls Mills	1766	1770	1386	1807	1580	2239	2453	1356	1761	1594	1728	2154
Bluefield	630	1029	542	688	762	735	681	1012	785	636	758	592
Tazewell	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
DELIVER	J	F	M	A	M	J	J	A	S	O	N	D
CPH	6338	6893	4766	6267	6175	7060	6492	9456	6526	6719	7387	5999
RD	7536	7552	6086	7548	8076	7411	6132	6956	6012	6023	5849	4627
Bois	1090	923	832	1275	1071	1159	986	848	847	883	819	833
Amon	252	392	287	278	299	617	345	395	280	268	235	246
JR	716	479	410	239	243	404	360	416	449	458	579	277
Bishop	450	487	379	510	584	589	412	585	603	508	545	508
Falls Mills	1542	1416	954	1384	942	2087	973	1158	1142	1499	1304	1610
Bluefield	633	1531	415	876	811	661	423	546	712	648	545	541
Tazewell	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Exhibit 3.7. Adjusted and transposed Tazewell County water system flow data.

Operating Expenses from the FY 1998 Tazewell County PSA Revenue Statement (units are dollars)	
OPERATING EXPENSES:	
Purchased water expense	143,660
Water, fuel & power	61,423
Water treatment & chemicals	38,523
Water treatment, operation, maintenance, labor & materials	401,026
Operation & maintenance of lines and storage	7,197
Operation & maintenance of meters & services	12,902
Sewer fuel & power	36,1331
Sewer treatment & chemicals	4,488
Sewer treatment, operation, maintenance, labor & materials	153,395
Purchased services [sewer]	301,798
Maintenance, fuel & power [sewer]	561
Maintenance, operation, labor & materials [sewer]	186,029
Meter reading expenses	9,863
Customer records & collection expenses	66,276
Office supplies & expenses	44,155
Administrative salaries	135,833
Payroll taxes & benefits	193,769
Professional & contractual expense	92,820
Insurance	58,410
Miscellaneous & unclassified	9,559
Contribution to project	30,000
Depreciation	675,259
TOTAL OPERATING EXPENSES	2,663,077

Exhibit 3.8. Operating expenses from Tazewell County Public Service Authority 1998 financial report.

Operating Expense	FY 1998 Amount	Category Total
Principal Payments on Loans & Bonds	$253,840	note: x0.5
Insurance	$29,205	note: x0.5
FIXED PLANT		$283,045
Meter Reading Expenses	$9,863	
Customer Records & Collection Exp.	$33,138	note: x0.5
Office Supplies and Expenses	$22,078	note: x0.5
Administrative Salaries	$67,917	note: x0.5
Payroll Taxes and Benefits	$96,885	note: x0.5
Professional and Contractual Exp.	$46,410	note: x0.5
ADMINISTRATIVE AND CONTRACT		$276,291

Exhibit 3.9. Adjusted and categorized fixed costs for the Tazewell County water supply system.

Operating Expense	FY 1998 Amount	Category Total	Adjust for Tazewell
Purchased water	$143,660		
Water, Fuel & Power	$61,423		
Water Treatment Chemicals	$38,523		
Water Treatment O&M Labor & Material	$401,026		
WATER TREATMENT		$644,632	$642,803
Water Line O&M	$7,197		
Meter and Service O&M	$12,902		
O & M		$20,099	$20,042
Miscellaneous and Unclassified	$4,780	Note: x0.5	
MISCELLANEOUS AND UNCLASSIFIED		$4,780	$4,766

Exhibit 3.10. Adjusted and categorized variable costs for the Tazewell County water supply system.

Component	Number	Unit Cost	Total
Tank Units	12	$8,000	$96,000
Booster Units	4	$8,000	$32,000
Base Computer	1	$30,000	$30,000
Spares	(20% +)	--	$31,600
Design	(50%)	--	$64,000
Installation	(50%)	--	$64,000

Exhibit 3.11. Summary of remote monitoring additional fixed cost estimate.

3.2.3 User-Input Parameter Estimation

The model contains five user-input parameters - three remote-monitoring factor parameters and the annual interest rate(s) applicable to present-worth calculations for annual fixed or variable costs.

The remote-monitoring extent factor FX describes the extent of remote monitoring as a fraction of the maximum potential loss reduction. It is estimated based upon user interpretation of water supply system physical conditions, monitoring system configuration and information about historical loss locations.

As discussed above, the extent of remote monitoring modeled for the example application is major mechanical components only as explained in Section 2.2. This assumes twelve tank and four booster pump monitoring locations associated with the individual water systems as indicated by Exhibit 3.3. After the physical subsystem of the Tazewell County water system was understood, operating excursion history was reviewed based upon two sources. Water system plans and operator recollection confirmed that water losses were distributed sufficiently uniformly among the individual water systems to allow application of a single remote-monitoring extent factor to represent the entire water system, leading to estimation of the parameter value at 0.30.

The remote-monitoring frequency factor FT is a model-calculated parameter that is a function of the remote- and manual-monitoring frequencies Tm and Tr input by the user. The manual-monitoring frequency Tm is the average frequency of routine mechanical component monitoring with manual monitoring, estimated for the subject water system at one (1) per day, and the remote-monitoring frequency Tr is the average frequency of monitoring with remote monitoring, estimated at twelve (12) per day, the value used to represent real-time monitoring with allowance for operator down time or other lag-causing events.

The interest rates used to calculate present-worth values are also user-input parameters. The interest rate associated with fixed costs was calculated as the dollar-weighted average of outstanding bond interest rates, which gave a value of 3.6 percent average annual interest. (Hicok and Fern, 1998) The interest rate associated with variable costs was calculated based upon the consumer price index for all urban consumers and industrial commodities less fuels, which gave a value of 2.0 percent average annual increase. (U.S. Bureau of Labor Statistics webpage, 2002)

3.3 Results

3.3.1 Break-Even Analysis

Spreadsheets 1 through 5 and the two break-even charts, presented as exhibits 3.12 through 3.18, show the results of the example application. Spreadsheet number 5 (Exhibit 3.16) presents the numerical output from which the break-even charts are created.

As the break-even charts show, with remote monitoring of major mechanical components at the supervisory level of automation, the model predicts break-even for the Tazewell County water supply system at approximately fifty-five percent of annual capacity (116,338,000 gallons delivered), which corresponds to an approximate total annual operating cost of $1,043,370. This break-even point is well within the water system’s model-defined operating range of approximately 211,000,000 gallons with associated $1,367,000 total operating cost (with manual monitoring).

When manual monitoring is replaced with remote monitoring, annual fixed costs are increased from approximately $644,000 to $690,000, and the unit variable cost measured by the variable cost parameter decreases from $3.43/1000 gallon to $3.04/1000 gallon, accounting for a total annual operating cost reduction of $37,200 at the system’s model-defined operating limit. This annual operating cost reduction gives a payback period of nine (9) years for a $317,600 total investment in remote monitoring.

3.3.2 Sensitivity

Sensitivity analysis was performed by observing how the break-even point moves in response to artificially varying the value of the remote-monitoring extent parameter. Three sensitivity runs were performed by comparing the resulting break-even points as shown on exhibits 3.19 through 3.21 to that of the original model run shown on Exhibit 3.18.

The sensitivity analysis runs incorporated the following changes.

(1) Sensitivity Analysis 1 – FX forced to 0.2 from 0.3

(2) Sensitivity Analysis 2 – FX forced to 0.4 from 0.3

(3) Sensitivity Analysis 2 – FX forced to 0.8 from 0.3; also indicates increased fixed cost for remote monitoring

Sensitivity run 1 demonstrates the effect of a lesser extent of remote monitoring (FX = 0.2). This increases the operating rate at which break even occurs to approximately 168,000,000 gallons (Exhibit 3.19), still well within the water system's model-defined operating range. Replacing manual monitoring with remote monitoring reduces the unit variable cost from $3.43/1000 gallon to $3.16/1000 gallon, which accounts for an annual operating cost reduction of $11,848 at the system's model-defined operating limit of approximately 211,000,000 gallons. For this sensitivity run the payback period increases to twenty-seven (27) years, reflecting decreased annual loss reduction and cost saving resulting from the decreased extent of remote monitoring.

Sensitivity run 2 demonstrates the effect of a greater extent of remote monitoring (FX = 0.4) while still monitoring only major mechanical components. This decreases the operating rate at which break even occurs to approximately 88,965,000 gallons (reference Exhibit 3.20), which makes remote monitoring cost effective at a lower operating rate than for the example application. Replacing manual monitoring with remote monitoring reduces the unit variable cost from $3.43/1000 gallon to $2.92/1000 gallon, which gives an annual operating cost reduction of $60,672 at the system's model-defined operating limit. For this sensitivity run the payback period decreases to six (6) years, reflecting increased annual loss reduction and cost saving resulting from the increased extent of remote monitoring.

Sensitivity run 3 demonstrates the effect of incorporating remote monitoring for distribution piping in addition to major mechanical components (FX = 0.8). Inclusion of remote monitoring for distribution piping implies increases annual remote monitoring additional fixed cost from $45,371 to $116,857. This simulation indicates break-even at an approximate annual operating rate of 132,792,000 gallons compared to the example application (FX = 0.3) break-even point of 116,338,000 gallons (reference Exhibit 3.21). This break-even point is also well within the water system's model-defined operating range of approximately 211,000,000 gallons. Replacing manual monitoring with remote monitoring increases annual fixed costs from approximately $644,400 to $761,200, and decreases unit variable cost from $3.43/1000 gallon to $2.55/1000 gallon, accounting for an annual operating cost reduction of $68,089 at the system's model-defined operating limit. The corresponding payback period increases to twelve (12) years, reflecting opposite effects of both increased cost of remote monitoring and increased annual loss reduction and cost saving resulting from the increased extent of remote monitoring.

Exhibit 3.12. Example application run spreadsheet number 1.

Exhibit 3.13. Example application run spreadsheet number 2.

Exhibit 3.14. Example application run spreadsheet number 3.

Exhibit 3.15. Example application run spreadsheet number 4.

Exhibit 3.16. Example application run spreadsheet number 5.

Exhibit 3.17. Example application run break-even chart 1.

Exhibit 3.18. Example application run break-even chart 2.

Exhibit 3.19. Sensitivity run 1 (FX = .2) breakeven chart.

Exhibit 3.20. Sensitivity run 2 (FX = .4) break-even chart.

Exhibit 3.21. Sensitivity run 3 (FX = .8) break-even chart.

3.4 Discussion

3.4.1 Remote Monitoring Cost Effectiveness

The parametric simulation model was applied to evaluate cost effectiveness of remote monitoring for the Tazewell County, Virginia water supply system based upon year 1998 production and financial data. The extent of remote monitoring designated for the model run was major mechanical components only, although sensitivity analysis was performed with other remote-monitoring configurations that included remote monitoring of distribution piping in addition to major mechanical components.

The Tazewell County water system in 1998 consisted of eight individual water systems (excluding the Town of Tazewell system) with twelve (12) tanks and four (4) booster stations serving a population of about 44,000. This system produced approximately 310,000,000 gallons with an approximately thirty-two percent loss rate resulting in about 211,000,000 gallons delivered to customers with an associated total estimated 1998 operating cost of $1,366,979.

The model simulation describes remote-monitoring cost effectiveness as a break-even chart that depicts a break-even point as the intersection of total operating costs as functions of water delivery with manual monitoring and remote monitoring. The primary model parameters are the unit variable production costs for the water system with manual or remote monitoring. The manual-monitoring variable cost parameter was calculated utilizing data from the Tazewell County Public Service Authority water production records and the 1998 Tazewell County Public Service Authority financial report. The remote-monitoring variable cost parameter is calculated by adjusting the manual-monitoring variable cost parameter through three factors that describe water delivery efficiency improvement attributable to remote monitoring. The difference in total operating costs is based upon the difference in the variable cost parameters and additional fixed costs for remote monitoring.

Generally, production and financial data received from the Tazewell County Public Service Authority were not suitable for input as received because they were incomplete or required reduction and/or reformatting. Also, preliminary review of water system physical characteristics revealed idiosyncrasies that made it impossible to determine water loss volumes from the Tazewell water system, and therefore both production and costs attributable to this individual system were excluded from the run.

Flow data consisted of monthly volumes produced, adjusted and sold to customers by individual water system. Prior to calculating loss volumes and transposing the resulting data by individual system to enable direct input to the model, it was necessary to determine the relationship between volumes reported as produced, adjusted and sold. After this was determined, missing data were estimated using a two part linear interpolation function based upon monthly variations and data sets with complete information from other years. This resulted in complete data sets which became model input.

Sources of financial information consisted of the 1998 Tazewell County Public Service Authority financial report and water and sewer system operating account records, although only the financial report was ultimately used as a source of input. Data were grouped into categories of fixed and variable costs to represent annual system operating costs. The source of all costs for these categories, except a portion of the category *fixed plant* was the revenue statement of the financial report. The portion of fixed plant defined as principal payments on debt came from the cash flow statement of the financial report. Variable costs were all taken from the revenue statement of the financial report.

Determining the value of fixed plant required analysis of the Public Service Authority's accounting practices, particularly with regard to depreciation. The annual value of fixed plant may be defined in various ways depending upon how capital funding and depreciation are handled. In general, depreciation will not be funded for a public entity and this is true for the Tazewell County Public Service Authority. Therefore, fixed plant was defined as the sum of insurance and principal payments on loans and bonds.

Additional fixed costs for remote monitoring were estimated based upon vender estimates and engineering judgement. Total cost for each category was estimated and entered into the model along with the estimated useful life for the category, from which the model calculates annual total cost. The cost categories include costs for system components, design and installation.

Simulation of the Tazewell County water system indicates a potential maximum annual savings of approximately $37,200 with remote monitoring of only major mechanical components, and a potential annual savings of approximately $68,100 when remote monitoring also includes distribution piping critical locations. For remote monitoring of major mechanical components only, the operating cost reduction gives a payback period of nine (9) years from a $317,600 total investment, while the payback period increases to twelve (12) years when the extent of remote monitoring is increased to include distribution piping.

When simulation results for the Tazewell County water system including remote monitoring of distribution piping are considered, it must be noted that the model was developed specifically for simulating operating costs of water systems with remote monitoring of major mechanical components only. Simulation results with the extent of remote monitoring increased to include distribution piping were performed as part of the sensitivity analysis to provide general information and are consequently considered less accurate than simulations based upon remote monitoring of major mechanical components only, due to uncertainty in estimating FX for this type of monitoring configuration.

3.4.2 User-Input Parameters

In addition to describing remote monitoring cost effectiveness for the Tazewell County water supply system, the application revealed two sets of important model characteristics. The first consisted of structural characteristics that were revised during final debugging. The second consists of user-input parameter nuances that must be recognized for model application. The user-input parameters, FX, Tm and Tr, and present worth interest rates, must be adequately estimated by the user because of their critical action in the model. During the example application much effort was expended to establish values for these parameters, and the application served as a means to study methods of making these estimates.

FX, the remote mode extent factor, describes the extent of remote monitoring considered for the subject water system. The model application served as mechanism for determining the various extents to which remote monitoring might be established as well as a test for the appropriate ranges for the values of this parameter. This was done by examining water system plans and schematics, and historical loss data to determine loss locations that correspond to the anticipated extent of remote monitoring. The expected delivery efficiency improvement that could be expected by implementing remote monitoring at each of these extents then led to the appropriate range of parameter values.

Recalling that $Qr = Qm + (FL*FX*FT)$ and that $FT = (1 - Tm/Tr)$ it can be seen that the estimation of Tm and Tr is also important. Tm was estimated by examining system operating records and conducting operator interviews to establish a weighted average monitoring frequency. Tr was estimated as the lower value of remote monitoring frequency, or actually the lower frequency of operator interaction with the remote monitoring system, i.e., the lower frequency at which operators will review data.

Interest rates necessary for calculation of present-worth values were based upon either published annual rates or rates on actual outstanding debt, as applicable.

3.4.3 Model Accuracy

Prior to performing the sensitivity analysis, model accuracy was evaluated by comparing simulated total operating cost to actual water system operating cost based upon Tazewell County Public Service Authority billing rates. This comparison indicates that the parametric simulation cost effectiveness model is extremely accurate at estimating total operating cost. With manual monitoring, the model simulates a total unit operating cost of $6.48/1000 gallon. This compares to actual billing rates of $5.24/1000 gallon or $8.00/1000 gallon for “in-town” use up to 2000 or 4000 gallons per month, respectively, or $8.13/1000 gallon or $12.00/1000 gallon for “out-of-town” use up to 2000 or 4000 gallons per month. (Town of Tazewell, 2002)

Part IV – Conclusions and Recommendations

4.1 Introduction

This part presents brief conclusions and recommendations in four sections corresponding to the four principal topics addressed by this thesis: Remote monitoring technology, treated primarily in Section 1.2 as background information; the parametric simulation cost-effectiveness model, detailed in Part II; remote monitoring for the Tazewell County water supply system, discussed in conjunction with the results of the example application in sections 3.3 and 3.4; and remote monitoring for rural water systems, addressed specifically only in this part.

In addition to these four topics, the research goals and Project objectives included developing an understanding of risk in rural water systems and cost-effectiveness of remote monitoring as a risk-reduction method. During the research phase, investigation into the nature of risk in water systems led to defining risk in terms of water system delivery efficiency or potable water loss originating from operating excursions. More specifically, risk was defined as the monetary value of potable water loss prior to delivery to customers. The parametric simulation model was developed as a tool to assist water system decision makers and researchers evaluating the risk-reduction potential and cost implications of remote monitoring for rural water systems.

The conclusions presented here are based upon knowledge acquired through execution of the two Project phases: the research phase and the model development and application phase. When read sequentially, these conclusions also summarize the Project from background research through development and application of the spreadsheet-based parametric simulation cost-effectiveness model.

For each principal topic, conclusions communicate the primary knowledge acquired or result ensuing from the Project effort, while for each principal topic except remote monitoring technology, recommendations present considerations for enhancing the model, enhancing operation of the Tazewell County water system or making the model available to rural water system managers as a decision-support tool.

4.2 Remote Monitoring Technology

The effectiveness and cost effectiveness of remote monitoring has been demonstrated in numerous industries such as chemical and petroleum refining, and other large-scale applications where improved operational control has increased product yield and reduced operating cost. These applications include larger water supply systems where remote monitoring has improved delivery efficiency and customer service, and provided information for planning and design. (Chu, 1995) (Haught and Panguluri in Cotruvo, et. al., 1999) (Mastran, 1999)

Water system remote monitoring is generally selected to perform one or more functions that may include monitoring or monitoring and remote control from a centralized location. It is also possible to select monitoring systems to diagnose system problems remotely and satisfy regulatory record keeping and reporting requirements. (Haught and Panguluri in Cotruvo, et. al., 1999)

Although distinct benefits and cost advantages have been reported for remote monitoring of industrial processes and larger water systems, prior to this Project there was no documented tool or specified method for evaluating cost effectiveness of remote monitoring for rural water systems.

4.3 Parametric Simulation Cost-Effectiveness Model

The Project was implemented with the specific objective of developing a spreadsheet-based parametric simulation model to evaluate this type of cost effectiveness. The model is a decision-support and research tool that can be utilized by water supply system decision makers or researchers for financial planning or comparative analyses about remote monitoring cost implications. Planning for remote monitoring can be aided by employing the model to perform a break-even analysis for a specific water system and remote-monitoring configuration, while comparative analyses can be conducted by varying remote-monitoring system configuration thereby yielding output that shows a variation of risk reduction and break-even conditions associated with different configurations. When utilized in conjunction with other relevant financial tools, such as payback analysis, the model can provide valuable information for capital improvement planning.

The model is accurate for water systems of size and configuration similar to the Tazewell County, Virginia water system, which served as an information source, particularly for determining critical user-input parameter value ranges for the remote-monitoring extent factor - FX, the manual-monitoring frequency - Tm and the remote-monitoring frequency - Tr. To maintain model accuracy for application to water systems of sizes and configurations that differ substantially from that of the Tazewell County system, the value ranges of the user-input parameters should be reevaluated. The model is based upon the supervisory control level of automation, which specifies operator directed system control, usually from a centralized location.

The model performs a graphic break-even analysis that shows the water system operating rate above which remote monitoring will be cost effective, i.e., the operating rate above which total operating cost for remote monitoring will be exceeded by total operating cost with manual monitoring. User-friendly features include the spreadsheet format and easily obtainable input data consisting of water system operating and financial information.

The model can be utilized in two basic ways. It can be employed directly to determine the break-even point for a contemplated remote monitoring system, or it can be employed interactively to enable the user to conduct an “optimization study” for various remote monitoring configurations for a particular water system. This type of study would involve multiple model runs with different monitoring locations, and analyzing the results to weigh the cost advantages and disadvantages of each.

With appropriate selection and, if necessary, adjustment of input data, the model is sensitive to the user-input parameters FX, Tm, Tr and present-worth interest rates - i. Of these, Tm, Tr and i can generally be estimated easily with a reasonably high degree of accuracy. Estimating FX with reasonable accuracy will often entail more user effort, but even this should not be cumbersome to a user with a reasonable amount of background knowledge.

Model sensitivity can be examined by observing how simulated total operating costs and the associated break-even point(s) are dependent upon the relative values of the manual-monitoring and remote-monitoring variable cost parameters - Vm and Vr, as they change in response to changes in user-input parameter values. This can be observed by artificially varying the value of FX, which is the user-input parameter judged to be most difficult to determine and therefore likely to be least accurate. It should be noted that, when FX is changed to the extent that it moves from the range applicable to monitoring all major mechanical components into the range applicable to monitoring strategic distribution conduit locations in addition to all major mechanical components, the additional fixed costs for remote monitoring must also be increased accordingly. Such an analysis is presented in Subsection 3.3.2 associated with the example application.

The model was developed to be a useful tool in its current state and to serve as the foundation of an enhanced simulation model or a more comprehensive MIS. An enhanced simulation model might feature automated, possibly GIS-based, parameter estimation to replace user input requirements in the current model, while a comprehensive MIS would serve water system management personnel by providing expanded data management capabilities that might include database/spreadsheet features designed to enable operating cost allocation and GIS features designed to aid remote monitoring system design and optimization. Parameters that could be estimated by an enhanced model are the remote monitoring extent factor FX, and the remote mode frequency factor FT.

In the current model risk is defined monetarily based upon the value of potable water produced by the water system under evaluation. Another useful way to enhance the model would be to enable other definitions of risk, such as the cost of water service interruption or regulatory non-compliance. The model could also be utilized to evaluate cost-effectiveness of other water system risk factors by assigning a monetary value to these and incorporating them into the model.

With regard to the simulation model, the following recommendations are made.

1. The model should be made available to rural water systems for evaluating risk-reduction potential and cost effectiveness of remote monitoring.

2. Should sufficient interest be indicated, the model should be refined to improve confidence and accuracy of results when evaluating remote monitoring that includes distribution systems in addition to major mechanical components (i.e., FX > .40).

3. After distribution of the model, user results and comments should be recorded and utilized to refine the model if appropriate and to re-estimate the user-input parameter ranges if necessary.

4.4 Remote Monitoring for the Tazewell County, Virginia Water Supply System

Applying the model to the Tazewel County, Virginia water supply system indicates a potential annual savings of approximately $37,200 with a payback period of nine (9) years for a $317,600 investment in remote monitoring of major mechanical components only.

It is recommended that the Tazewell County water system consider implementing remote monitoring of all major mechanical components if this expenditure is within the system's operating budget for the payback period.

Results from the sensitivity analysis also indicate a potential annual savings of approximately $68,100 with a payback period of twelve (12) years for $818,000 investment in remote monitoring when remote monitoring also includes distribution piping critical locations.

However, due to the lower accuracy of the data used in this run, it is recommended that further evaluations be conducted with more accurate estimates of fixed costs for additional remote monitoring based upon a detailed identification of critical distribution piping monitoring locations.

4.5 Remote Monitoring for Rural Water Supply Systems

Several conclusions can be formulated from results of the Project background research and model example application. In general, it appears that remote monitoring will be cost effective for rural water supply systems with operating rates above about 130 million gallons annual delivery when major mechanical components only are monitored. More research is necessary to be able to make a similar statement about remote monitoring when distribution piping is included. Remote monitoring also appears to offer other benefits that were not quantified by the model, such as improved personnel utilization and other cost savings.

An important result of the Project is the realization that the cost and benefits of remote monitoring for rural water systems must be evaluated on an individual basis. Unlike larger systems, where the benefits of remote monitoring are almost certain to outweigh the costs, rural systems appear to be of varied characteristics such that individual analysis necesary. These characteristics include operational history, size and number of individual systems, geography and fiscal considerations. This latter characteristic also means that the use of a break-even model alone may give insufficient information for deciding whether to implement remote monitoring, and that information from other financial analyses such as payback period may need to be considered within the context of the system's financial environment.

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