Goal Programming For Sustainability In Total Water Management

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By

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DEDICATION

This is dedicated to my grandmother, Gladine Liner, who is a champion for education, as demonstrated by her exceptional career in teaching, as well by being the first in the family to earn a Master's degree.

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ABSTRACT

GOAL PROGRAMMING FOR SUSTAINABILITY IN TOTAL WATER MANAGEMENT

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With the Triple Bottom Line (TBL) of Sustainability, total water management efforts must analyze alternatives to address the potentially conflicting goals of economics (financial), environmental, and social issues. Goal programming is a technique which uses optimization methods to provide a means to solve a problem by striving towards multiple objectives simultaneously. This research seeks to apply an optimization framework to the integrated water supply planning process. The research has developed a methodology to that can successfully generate a feasible set of alternative solutions while balancing all three goals of the TBL.

Performance measures for each of the three goals (economic, environmental, and social) are the core building blocks to enable analysis of total water management plans. Generally, economic goals are well understood and defined. Over the past decade, environmental goals have been developing enhanced understanding and usage. Special

attention will be paid to the third pillar of sustainability – social, which is generally agreed that measures are lacking. A targeted survey of industry experts indicated that the social sustainability metrics showing the most promise for use are related to affordability, reliability, and resilience.

Furthermore, the research showed that the goal programming methodology could use existing data (utility master plans) and tools (Excel) to execute the model and develop tradeoffs between the various aspects of the TBL. In the demonstration with real world utility data, examples are shown detailing the relative costs for enhanced environmental and social goal achievement. The methodology has the potential to provide increased visibility to cost, societal and environmental issues for to the decision makers in order to enhance the decision analysis of water supply strategies by incorporating the environmental and social aspects of sustainability into the decision process.

1 OVERVIEW

Societies around the world are increasingly faced with problems involving the availability and distribution of natural resources. In the social psychological literature, these problems are referred to as social dilemmas because they represent a conflict between the collective interest of a society and the individual interests of its members (Vugt and Samuelson, 1999). Current trends in water-use activities and the resulting decline in quality of water bodies have threatened water availability. Even a decade ago, at The World Water Forum held in March 1997 in Marrakech, Morocco, experts predicted a water crisis by 2050 (Johnson, 1998). Water is a renewable but finite resource that is vital to human life. Two thirds of the world is covered by water; unfortunately fresh and accessible water accounts for less than a percent of the total. The quantity of water on the earth does not change but the amount of useful water is decreasing due to the adverse impact of the human activities (urbanization, industrialization, growing population, etc.)

Due to the improved living standards, the world water demand has been growing faster than its population. Per capita consumption is much greater than it was few decades ago. To date, this increasing demand was met mostly by the dam building and river diversion. Currently, the development projects have become increasingly complex, expensive to build, and more damaging to the environment (Postel, 2007). Reduced or polluted river flows can have multiple influences. One is to limit economic performances of an area through the destruction of fisheries and declining agricultural production. Besides scenic and recreational opportunities, healthy water resources allow natural systems to maintain their functions of buffering and filtering out pollutants, recycling organic materials and providing habitat for wildlife. Insufficient supply of drinking water can affect nutrition and health of the domestic users. Reduced water consumption does not only have economic benefits but it is also environmental friendly. Integrated water resources planning (IWRP) is an important strategic tool in managing this precious natural resource in a sustainable manner.

1.1 Problem Identification

Water waste, overuse and mismanagement are the causes of shrinking water reserves in many areas of the world. World Commission on Water (WCW) indicates that more than 50 per cent of world's major rivers are seriously depleted and polluted, poisoning surrounding ecosystems and threatening the health of tens of millions of people. Water scarcity is the single greatest threat to the global food production. The world's food supply would be threatened if water-use efficiency does not improve. According to a report by the World Commission on Water, presented at the 2nd World Water Forum in the Netherlands on March 2000, the amount of water needed to grow the world's food in the next two decades will outweigh what is available by about 17% (Water Crises, 2000).

Planning for water resources takes place at many different levels: globally (Millennium Development Goals, 2005), internationally or interstate by water basin (Colorado River, 2007), at the water provider (Means, Patrick, Ospina, and West, 2005), and at the individual consumer level. Municipal water utilities are in a unique position of having to comply with both the higher level demands coming from the global, national, and statewide constraints, and to meet the needs (or change the usage patterns) of individual consumers.

Traditional municipal water supply planning has historically focused on managing supply to meet consumer demand. Conservation and demand management were later added to the municipal utility's arsenal. In 1997, the American Water Works Association Research Foundation (AwwaRF) released its initial guidance on integrated resource planning, focusing on water quantity, water quality, and wastewater management responsibilities (Albani, 1997).

Water supply planning efforts are gradually gaining enhancements to incorporate uncertainty or formal decision analysis. The current best practice for the water industry incorporates scenario planning to identify a discrete set of possible outcomes – typically around five alternatives – each with a probability of occurrence (Means et. al., 2005). While scenario planning attempts to address uncertainty, the process can also lead to the development of multiple plans to be used depending on which alternative outcome occurs in the future.

Decision analysis techniques such as optimization and simulation are widespread throughout the water industry, however the application has been focused on treatment plant operations, distribution system operations, and large scale water basin or reservoir operations (Ormsbee and Lansey, 1994; Jentgen, 2005; Revelle, Joeres, and Kirby, 1969). The water supply planning function has used decision support techniques such as multi-attribute utility analysis and decision trees, but has yet to implement the tools that the plant and system operations functions have embraced for years (Huber-Lee, Swartz, Sieber, Goldstein, Purkey, Young, Soderstrom, Henderson, and Raucher, 2006).

The complexity of the water supply planning process is exemplified by the need to incorporate the "triple bottom line" of sustainability - economic (financial), social, and environmental concerns - into integrated water supply plans (Kenway, Howe, and Maheepala, 2007). The constraints imposed on municipal water supply planners to comply with higher level (state and regional) policies, manage user demand, address uncertainty such as climate change, and focus on the triple bottom line, highlight the need for these planners to have optimization tools such as goal programming techniques at their disposal.

1.2 Approach

The focus of this research is to create a general form of a goal programming model to enhance the analysis of sustainability measures in integrated municipal water supply planning. The focus will be on refining the definition of the tasks used in the integrated planning process and enhance the plans through optimization and simulation techniques. By implementing a systems engineering approach to the planning, this research effort intends to demonstrate how a integrated water supply plan can be developed using industry standard methods (multi attribute utility analysis, decision trees, and scenario planning) can be enhanced through the utilization of optimization and simulation models to develop a more comprehensive plan.

Using this methodology, the general form of a goal programming framework will be developed to encompass the following:

- Goals: Addressing the triple bottom line (TBL) of society, cost, and environment
- Constraints: Addressing costs, demand forecasts, alternative sources, capacity and demand management

Real data and plans from a municipal water utility is used as a means of demonstrating the feasibility of the approach.

1.3 Research Contributions

The primary contributions of this research will be fourfold:

- Demonstration of the application in the integrated municipal water resources planning process of optimization techniques used in other areas of water supply management (reservoir, treatment plant, and distribution system operations)
- Development of the general form of a goal programming framework to enhance problem and solution definition through formal decision analysis, including

definition of objective functions for optimization and definition of stochastic variables for simulation

- Demonstration that, when given the tools and knowledge necessary to make an informed decision, municipal utility decision makers can successfully balance the three potentially conflicting aspects of the triple bottom line without an overriding bias towards the financial component.

2 REVIEW OF PRIOR RESEARCH

The existing literature relevant to this research has been grouped into three basic topic areas:

- Accounting for sustainability in water supply planning
- Municipal water supply planning process
- Optimization models used in municipal water supply

2.1 Accounting for Sustainability in Water Supply Planning

Municipal water utilities are the primary implementers of water resources policies developed at all levels of government, from global to international to state and basin level regulations or policies. Generally, these policies are goal statements specifying “what” needs to be done, while the “how” the goal is reached is often thrust upon the municipal utility.

At the global level, the United Nations has identified eight Millennium Development Goals (MDGs). The seventh of which is to “Ensure Environmental Sustainability.” Under this goal, Target 10 states the following goal: “To halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation." (Millennium Development Goals, 2005) Two performance metrics have been developed for this goal:

- Proportion of population with sustainable access to an improved water source
- Proportion of population with access to improved sanitation

The Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lakes Powell and Mead (2007) provide an example of multi state and international guidance. Commonly called the Seven States initiative, the effort involves all seven States in the Colorado River basin: Arizona, California, Nevada, Wyoming, Utah, Colorado, and New Mexico. The guidelines address total water resources goals and alternatives for the entire basin, including Mexico. Both quantity and quality (salinity differential) are involved in the agreement with Mexico as a partner in the effort.

2.1.1 Evolution of Water Supply Planning

Historically, water supply planning has been focused on determining the expected demand for water and developing or expanding sources (such as wells, reservoirs, and rivers) to meet the demands. Over the past two decades, the water industry has focused on integrating water resources, including, supply, demand, disposal (wastewater), and other environmental and social issues. Contemporary water supply planning efforts explicitly demonstrate these concepts through the use of terms such as Integrated Resource Planning, Integrated Water Supply Planning, Integrated Water Supply

Management, and Total Water Management (Albani, 1997; Binney, 2006; Integrated Water Cycle Management, 2006; Patwardhan, Baughman, Tyagi, and Thorpe, 2007). The high level goals and strategies shown above (MDGs and Seven States) demonstrate the integration. The MDGs specify both water supply and sanitation and the Seven States effort focuses on conservation, reuse, and even air quality.

The United States Department of Interior has cited water shortages in the United States as one of the top five environmental issues. The present concerns for dependable water supplies have resulted in a paradigm shift in the water resource management policy, from exploring new surface and groundwater sources to one of conservation and alternative source identification (Maddaus, Gleason, and Darmody, 1996). Investments in conservation, efficiency, reuse, and recycling can yield more usable water per dollar than investments in new engineering projects to expand the freshwater supply. Water conservation through demand management refers to water use practices and technologies that provide the services desired by the users while using less water. The water needs are not being compromised, however, the emphasis is upon the efficient and wise use of water. Water conservation is the means for achieving improvement in water-use efficiency and thus reducing the impact of human on water resources (Dziegielewski, 1996)

Reflecting this growing international shortage, water and sewer rates showed a sharp increase over the past 20 years, often outpacing inflation in many countries. According to a World Bank report, the cost of engineering and developing new water sources is so uneconomical that the water supplied by these new future projects will cost the consumers two to three times more than the cost of current supplies (Postel, 2007).

As water supply planning evolved to encompass both supply and demand management as resources, the water industry began considering non-traditional sources of water, as well. In her article “Preserving Sustainable Water Supplies for Future Generations,” Kenel posits that alternative sources should always be considered in the development of an integrated water supply plan (Kenel and Schlaman, 2005). These alternative sources have evolved from desalination of brackish or saltwater to greywater reuse, to reclamation of treated wastewater.

Following this evolution, AwwaRF has embraced the consideration of these alternative sources during the early to mid 2000s. In 2007, the research foundation released a Protocol for Developing Water Reuse Criteria with Reference to Drinking Water Supplies (Warner, 2007). In the next few years, the studies will encompass even more innovative techniques such as aquifer storage and recovery of reclaimed wastewater for use as raw water for drinking water supplies (Potential and Pitfalls, 2009).

Besides the use of water in agriculture, industry, and cities, water is also needed to dilute pollution, generate electricity, protect fisheries and wildlife and for navigational purposes. More water for human needs is leaving less for sustenance of ecosystem. Inefficient water use leaves less water in streams for fish. In many areas a great number of aquatic species are endangered. Many species of fish, worthy for recreation, commercial, and biological use, are at a risk because of the habitat destruction (Postel, 2007). A reduction in water use can maintain the stream flow levels necessary for the welfare of river systems. Human health, economic development, and the diversity of the ecosystem will be at stake if the resource gets exhausted. The reduced consumption as the sole criterion for a program selection can't justify the excessive costs associated with the implementation of the program in case of a minimal amount of water savings if other not less important factors are ignored in the analysis. Therefore water supply system should be considered as a part of a complex environmental system by addressing economical, environmental, social, and other relevant issues associated directly or indirectly with the supply system.

In the late 1990s, the American Water Works Association Research Foundation (AwwaRF) funded many research projects involving an overarching concept called Total Water Management (Patwardhan et. Al, 2007; Young, 2006). Two especially significant studies included the discussion of the constraints facing new or expanded water source development (Wubbena and Hathhorn, 1999) and the development of industry guidance on Integrated Resources Planning (IRP) (Albani, 1997).

The IRP guidance document provided industry standards for recommended best practices for IRP. These practices included consideration of supply and demand management, public involvement, risk management, and a broadened scope of goal setting and evaluation criteria. Table 1, below, displays a summary of selected facets of how IRP enhances the traditional water supply planning (Water Resources Planning, 2007).

Table 1: Comparison of Traditional Water Supply Planning and Integrated Resources Planning

Factor	Traditional Water Supply Planning	Integrated Resources Planning
Resource Considerations	*Supply Options Only*	*Demand and Supply Options*
Cost Considerations	*Utility Costs*	*Multiple perspectives (society, ratepayers, environment, program participants*
Involvement in Planning Effort	*Utility Staff and limited departments*	*Broad utility participation, outside experts, board members, public*
Role of Public	*Intervener*	*Participants*
Objectives and Criteria	*Minimize costs to utility and maintain system reliability*	*Multiple objectives based on diverse criteria such as environmental quality and economic development*
Approach to Risk	*Avoidance*	*Managed*
Planning Horizon	*Near term to meet Capital Improvement Plan (CIP) needs*	*Long term (50-100 years)*

As the IWRP process has evolved, enhancements and modifications have occurred. Hooper (2006) discusses governance and best practices in IWRM, as well as research needs, while Chestnut, et. al. (2007) helped AwwaRF develop a water conservation extension to the industry recommended integrated water management guidance.

2.1.2 Sustainability

As water resources planning moved from supply side only to incorporation of demand management and alternative sources, the goals for the plan, and the criteria on which they were judged, also expanded, as the term "sustainability" emerged as an integral theme. Kenel and Schlaman discuss the social aspect of IWRP, explicitly linking sustainability in water supply to the needs of future generations (Kenel and Schlaman, 2005). The Global Water Partnership defines integrated water resource management as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the ***sustainability*** of vital ecosystems." (Jonch-Clausen, 2004) This definition is demonstrated by a number of sustainability related issues that have come to the forefront of utility management, including:

- User base growth coupled with constraints on water supply quantity and quality

- Aging infrastructure and high costs (both capital and operations and maintenance, O&M) of repair and replacement

- Climate change – both impacts of climate change to utility (changes in water supplies) and impacts of utility actions on climate change (carbon footprint from emissions and energy usage)

In order to address these issues in goal setting, the Triple Bottom Line (Social, Economic, and Environmental) accounting protocol can be used. The figure below provides an example of a representation of the TBL framework (Kenway et. al. 2007).

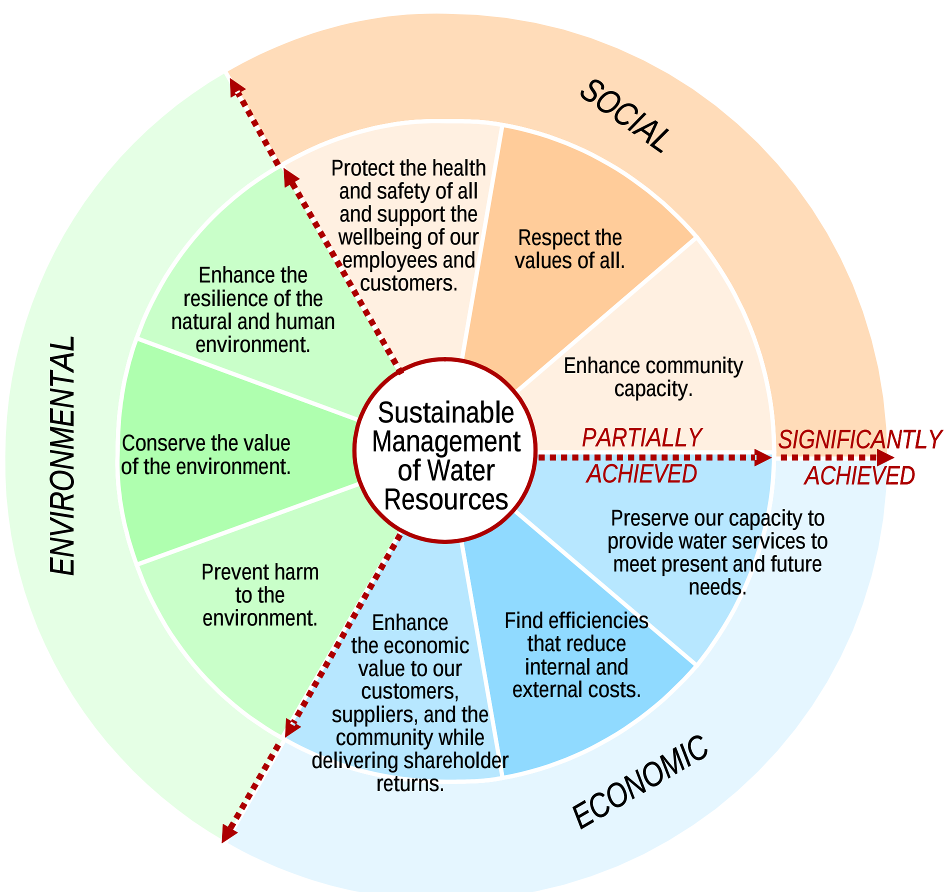

Figure 1. A Triple Bottom Line Framework

The TBL concepts are evident in AwwaRF's Decision Support System for Sustainable Water Supply, a tool developed to aid water supply planners and incorporated the potentially conflicting economic, environmental, and social goals (Huber-Lee et. al., 2006).

The TBL framework is applicable at even the most rudimentary water systems. With the focus on progress towards the Millennium Development Goal of providing "safe, sustainable access to drinking water" in the lesser developed countries, the World Bank's Water and Sanitation Division developed a set of performance metrics to help evaluate the state of a county's water industry (Millennium Development Goals, 2005). These measures, and their relation to the TBL are listed below:

- Economic Sustainability Indicator: Working ratio (expenses divided by revenues) of water provider

- Social Sustainability Indicator – Population practicing hygienic use of sanitation facilities

- Environmental Sustainability Indicator – Number of functioning water supplies

2.2 Municipal Water Supply Planning Process

This section discusses the process of municipal water supply planning, beginning with the industry management best practices, comparison to an out-of-industry analog, and specific subprocesses used in the industry.

2.2.1 High Level Framework

As IWRP incorporates a broad spectrum of water utility management and operational subjects, the industry best practices for utility management were reviewed. The American Water Works Association (AWWA) and the Water Environment Federation (WEF) have implemented a program entitled QualServe in order to best practices in management in the water and wastewater utility industry (Ginley, 2006). QualServe is a systems engineering approach to produce a consistent means to evaluate utility efforts and to aid utilities are reporting key performance indicators to regulators and the public. While QualServe seeks to put a systems engineering structure on overall utility management, the IWRP processes are spread between multiple business systems including:

- Water Resources Management
- Water Quality Management
- Capital Improvement Plan
- Strategic Plan
- Watershed Management
- Air & Water Quality Permitting

Often, reviewing a similar, but out-of-industry, example can lead to new insight into an organization's processes. The Capability Maturity Model Integration (CMMI) from the Software Engineering Institute (SEI) is an out of industry analog to QualServe (Chrissis, 2007).

While CMMI originally focused on the development and implementation of software, hardware, and systems, CMMI is used extensively in the automotive and defense industry as a set of standard processes used to ensure repeatability and reliability of systems. In addition, the design of CMMI is intentionally generic to aid in the use of the systems engineering practices in multiple industries (Miller and McHargue, 2001). CMMI is set up similar to QualServe in that the business functions and lifecycle are broken down into a defined set of process areas.

As an expansion to the CMMI framework, the model has been expanded into constellations for various uses: CMMI-DEV for software development, CMMI-ACQ for acquisition, and CMMI-SVC for service industries (Chrissis, 2007). With a process area explicitly targeting capacity planning (and the relevance to integrated water resources planning), the CMMI-SVC framework is most analogous to QualServe (QualServe, 2008). The process area *Capacity and Availability Management (CAM)* from CMMI-SVC concerns itself with ensuring that sufficient resources are in place to meet the demands – analogous to developing an integrated water supply plan (CMMI for Services, 2007). The Specific Goals and Practices for the CAM process area are shown in Figure 2, while Figure 3 shows all of the process areas for both QualServe and CMMI-SVC.

Goal 1: Prepare for Capacity and Availability Management

- SP1.1 Establish a Capacity and Availability Management Strategy
- SP 1.2 Select Capacity and Availability Management Measures and Analytic Techniques
- SP 1.3 Establish the Service's Baselines and Models

Goal 2: Analyze and Monitor Capacity and Availability

- SP 2.1 Analyze and Monitor Capacity
- SP 2.2 Analyze and Monitor Availability
- SP 2.3 Report Capacity and Availability Management Data

Figure 2: Capacity and Availability Management from CMMI-SVC

QualServe

Business Process Category	Business System
Business Planning & Management	Capital Improvement Plan Strategic Plan Financial & Fiscal Management Plant & Real Property Management Engineering Purchasing Information Management System
Customer Relations	Customer Service Customer Strategy & Satisfaction Customer Accounts Management Government, Business & Community Relations
Organization Development	Leadership & Organization Continuous Improvement Human Resources Management Health & Safety Management Emergency Planning & Response
Wastewater Operations	Watershed Management Collection System Operations & Maintenance Treatment Operations & Maintenance Industrial Pretreatment Program Biosolids Management Permitting/Air & Water Quality
Water Supply	Water Resources Management Treatment Operations & Maintenance Distribution Operations & Maintenance Water Quality Management

CMMI - SVC

Process Category	Process Area
Process Management	Organizational Innovation and Deployment (OID) Organizational Process Definition (OPD) Organizational Process Focus (OPF) Organizational Process Performance (OPP) Organizational Service Management (OSM) Organizational Training (OT)
Project Management	Capacity and Availability Management (CAM) Integrated Project Management (IPM) Project Monitoring and Control (PMC) Project Planning (PP) Requirements Management (REQM) Risk Management (RSKM) Quantitative Project Management (QPM) Service Continuity (SCON) Supplier Agreement Management (SAM)
Service Establishment and Delivery	Incident Resolution and Prevention (IRP) Service Delivery (SD) Service System Development (SSD) Strategic Service Management (STSM) Service System Transition (SST)
Support	Causal Analysis and Resolution (CAR) Configuration Management (CM) Decision Analysis and Resolution (DAR) Measurement and Analysis (MA) Process and Product Quality Assurance (PPQA)

Figure 3: CMMI Framework as Compared to QualServe

While the QualServe framework spreads the integrated water supply planning functions across multiple process areas, the CMMI-SVC model limits capacity planning to one area. Practice 1.2 (Select Capacity and Availability Management Measures and Analytic Techniques) combines the criteria determination and evaluation into one practice.

2.2.2 Detailed Water Resources Planning Methods

Practices similar to those identified in the approach to capacity planning in CMMI-SVC have been used in water resources. An organization specializing in water resources dispute resolution has developed a systematic approach to solving water resources problems. Steps 1 through 3 of the resolution methodology correspond to Specific Practice 1.2 of CAM (Select measures and analytic techniques). Steps 4 and 5 correspond to Specific Practice 1.3 (Establish baselines and models). Step 6 is analogous to Specific Practice 2.1 (Analyze capacity) and Steps 7 and 8 correspond to Specific Practice 2.3 (Report capacity management data). Figure 4 displays this approach.

- Step 1: Develop Performance Measures that represent the objectives for the project or study.
- Step 2: Identify Data Available For Use in generating the performance measures when alternatives are evaluated.
- Step 3: Achieve Consensus On Evaluation Methodology
- Step 4: Agree On Types Of Alternatives To Be Evaluated
- Step 5: Design Analytical Tools that will be required to generate the performance measures.
- Step 6: Analyze Alternatives from a systems point of view.
- Step 7: Select a non-inferior solution or set of solutions.
- Step 8: Develop Implementation Strategy

Figure 4: Water resources resolution methodology (Systematic Approach, 2008)

While IWRP does encompass many areas of water utility management, the fundamental purpose of the water supply planning effort is supplying enough water to meet the demand. In the Water Supply Manual of Practice, AWWA focuses on this purpose, but the manual does specify a process for Integrate Resources Planning, as shown in Figure 5. This research will build upon the IRP process displayed in Figure 5 in order to build the general form of the goal programming model for sustainability in integrated water resources planning.

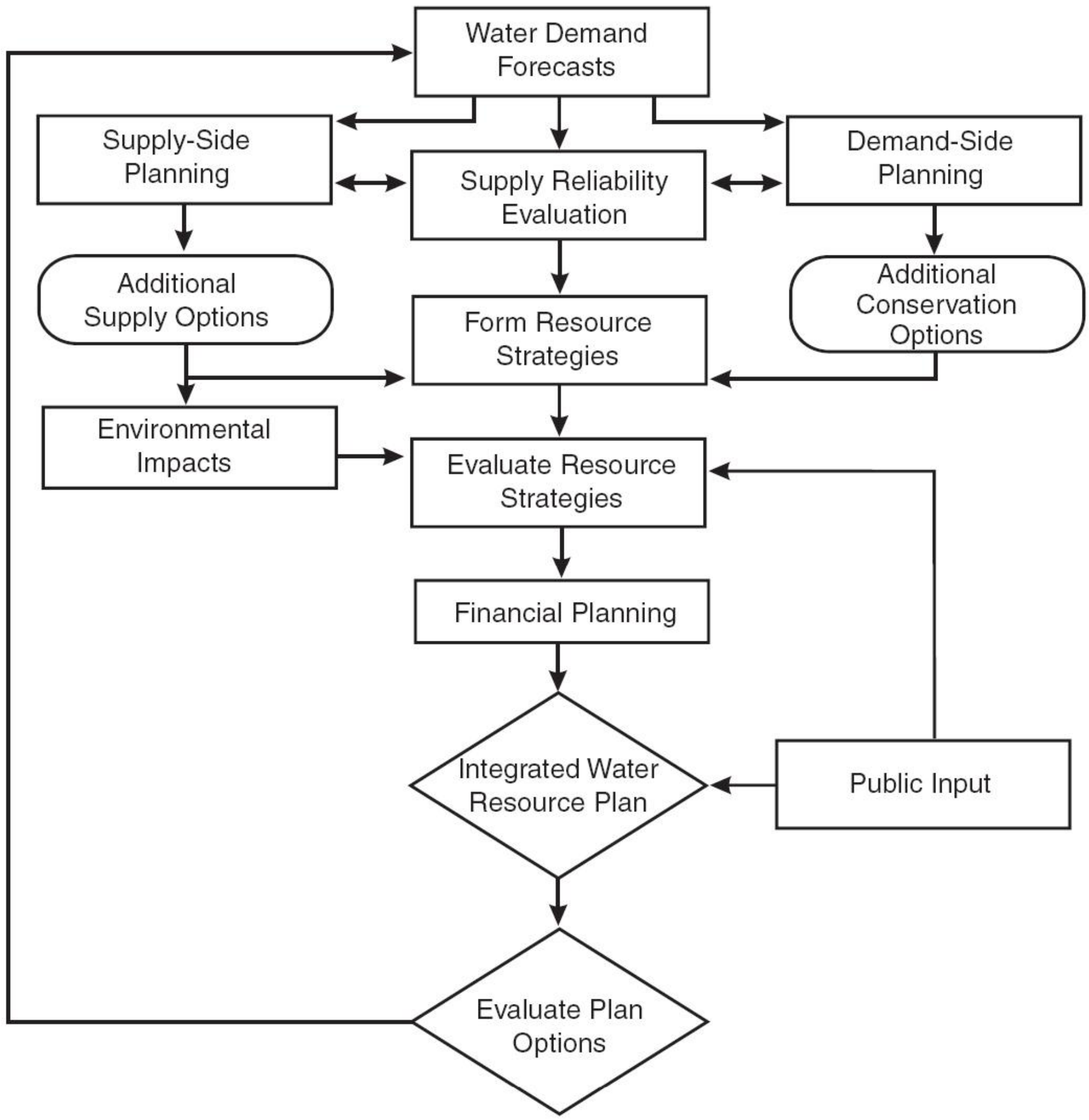

Figure 5: AWWA Recommended IRP Process (Water Resources Planning, 2007)

2.2.3 Evaluation of Alternatives

The industry guidance for evaluating resource combinations is to first enumerate a set of scenarios or sequences. Once the feasible alternatives are identified, cost effectiveness studies and benefit/cost analyses are recommended (Water Resources Planning, 2007).

2.2.3.1 Benefit Cost Analysis

Economic theory posits that a full accounting of all intended and unintended benefits and costs will direct the decision maker to the appropriate choice when compared to other alternatives. Specifically, economic theory directs a decision maker to select the project producing the greatest net increase in the value of goods or services. Thus, economics provides a means to focus on the economic efficiency aspects of one or more projects and benefit-cost analysis is the framework within which economic efficiency is evaluated and reported.

Project benefits and costs are typically classified as either direct or indirect. Direct benefits and costs are those effects produced directly from the project. Examples of direct benefits accrued from a project involved in IWRM might include the reduction in waste effluent or discharge into a receiving body of water or the reductions in the withdrawal from a water supply leaving additional water for in-stream uses. Indirect benefits and costs are those that correspond to changes in the value of overall production in the economy. Indirect benefits accrued from the alternative might include increased use of a water body for recreational purposes given the increase in available water for in-stream uses such as fishing. Both direct and indirect benefits and costs can be further classified as tangible (those easily quantifiable) and intangible (those not easily quantifiable). Figure 6 shows the continuum which demonstrates some of the limitations in benefit cost analysis.

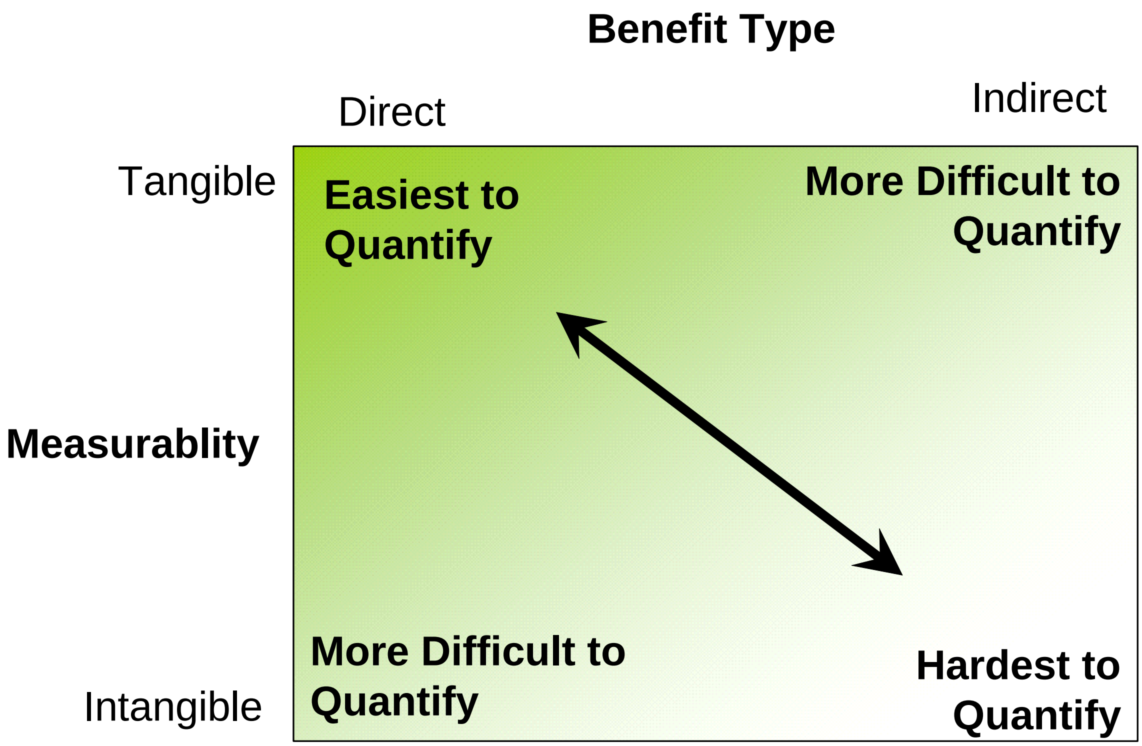

Figure 6: Difficulty of Quantifying Benefits

A complete accounting of all project effects, both direct and indirect and tangible and intangible poses significant challenges. Such an analysis is referred to as a general equilibrium analysis because it considers all direct and indirect effects realized in the economy. From an economics perspective, however, many of the indirect effects, because they are by definition unintended, can produce benefits to one party while imposing costs on another. As a result, many of the unintended benefits and costs will cancel each other out. Though a detailed understanding of all project benefits, both direct and indirect, may prove useful to the decision maker for articulating the range of effects conveyed to each project stakeholder, the actual cost and duration of the data collection could be prohibitive relative to the value of the information provided. As a result, economists consider a benefit-cost analysis that focuses primarily on the direct outputs of a project to be a reasonably precise estimate of project benefits and costs. Such an analysis is considered a partial equilibrium analysis because it considers only the direct effects.

An integral part of integrated water supply plans, conservation programs are often capital intensive requiring a large portion of water agency's total operating budget, thereby giving less encouragement to the water agencies to invest in such programs. Once water conservation measures are implemented, it is expected that the total water delivered to the system would decrease, thereby decreasing the net revenues of the utility. This 'net revenue impact' represents the lost income of the utility due to water conservation at the end-use. However, there are long term benefits realized by the deferment of capital-intensive projects (deMonsabert, Sullivan, and Liner, 2002).

Benefit/cost analysis, while widely used to evaluate demand-side (conservation) alternatives for their cost effectiveness or to justify the investment, is prone to cause errors in setting the optimal policy for its imprecise nature (Jenkins, Lund, and Howitt, 2003). The benefits are usually the potential water reduction causing further savings in terms of avoided cost of supply and treatment, delay in capacity investment, etc. A program can't simply be rejected on the basis of economic analysis if the benefit/cost ratio is less than one. Under program selection process that simply rank order programs based on benefit/cost ratios [economic analysis], the synergy between programs may be muted or lost (Rothstein, 1996).

2.2.3.2 Decision Support Systems

A long-term water supply plan generally consists of changes in water use systems and technology, behavioral change, and the regulatory standards. It is necessary to consider the impacts of a certain alternatives in a broader ecological and social context along with the economic considerations, hence the TBL framework. The statistical models, dealing with the environmental problems, are often incapable of formulating the non-linearities present in the nature. Generally the ecological and social models are oversimplified because they are very expensive otherwise or many times impossible to model (Rajabi, Hipel, and Kilgour, 1997).

Environmental system's modeling does not always have numeric values associated with its attributes. Instead of a purely benefit/cost analytical framework, a Decision Support System (DSS), in many cases, is more appropriate for such problems to compare the system's attributes in terms of their relative importance. It is not always prudent to judge a program's supremacy among others exclusively on the basis of its highest ranking. Selection of an alternative based on rank order may lead to a sub-optimal program combination. A DSS is a system intended to support decision-makers, by enhancing their capabilities, in semi-structured decision situation. DSS serves as a supplement to the decision making process when decision can't be completely supported by algorithms.

The municipal water supply industry has developed numerous decision support systems incorporating water supply (Develop a Dynamic DSS, 2010; Huber-Lee et. al., 2006), as well as addressing issues such as demand-side management (Integrated Water cycle Management, 2006) and piping system renewal (Deb, Hasit, Schoser and Snyder, 2002).

2.3 Optimization Models in Municipal Water Supply

Formal mathematical models help the decision-maker increase the consistency and rationality of his/her choices. The precise nature of these models provides an effective means of communicating the relative values assigned to each attributes of any alternative. The judgment and their underlying assumptions thus become explicit and subject to rational review (deNeufville and Stafford, 1971). While considering water supply system as a part of a complex environmental system, imposition of non-financial constraints along with the economics is inevitable. Environmental impacts and legal constraints are a few measures to account for. Meeting human needs while considering economic, social, ecological, and political limits requires developing a reasonably comprehensive system's modeling approach.

Optimization has been utilized in water resources management for decades.

However, when looking at the implementation of optimization techniques across project phase (Planning, Design, and Operations) and relevant scale (International, Basin Level, and municipal), the literature shows optimization usage in the planning phase has been focused primarily at the larger scale (International and Basin level), while optimization techniques have been implemented in design and operation at the municipal level. The grey areas in Table 2 show areas that have optimization references readily available for the combination of phase and scale. Note that International efforts are always listed as planning as the design and operations are typically implemented by basin or municipal level.

Table2. Literature Review on Optimization in Water Resources

	Planning	**Design**	**Operation**
International			
Basin/Regional			
Municipal/ Local	**0 References with Optimization**		

The following sections list the titles of the publications referenced in Table 2. In most cases, the coverage of optimization is evident in the title. In some cases the title describes a systems approach that includes optimization. In one case in municipal design, there is a paper entitled "Optimizing a Water Master Plan," but the publication actually concerns itself with the use of genetic algorithm to improve facility design and is therefore included in the design phase as opposed to the planning phase, for the purposes of this comparison (Frey, McCuller, Henke, Spackman, and Murphy, 2001).

2.3.1 International Planning

- Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead (2007)
- Water Resources Systems Planning and Management: An Introduction to Methods, Models, and Applications (Loucks, Revelle, and Lynn, 1967)
- Millennium Development Goals Report (2005)
- Water Crises Predicted for 2020 (2000)

2.3.2 Basin Planning

- A conceptual software system for water allocation, planning and catchment management (Argenta, Gijsbersb, Perraude, and Podgerc, 2006)
- Develop a Dynamic Decision Support System (D2S2) for Water Supply Planning in the Lower East Coast of Florida (2010)
- Network Flow Optimization Model for Basin-Scale Water Supply Planning (Hsu and Cheng, 2002)
- The Use of Object-Oriented Modeling for Water Resources Planning in Egypt (Simonovic, Fahmy, and El-Shorbagy, 1997)
- Systems Analysis in Ground-Water Planning and Management (Yeh, 1992)

2.3.3 Basin Design

- Optimization of Transfers in Urban Water Supply Planning (Lund and Israel, 1995)
- Reservoir Management in Potomac River Basin (Palmer, Smith, Cohon, and ReVelle, 1982)
- The Linear Decision Rule In Reservoir Management And Design. I. Development Of The Stochastic Model (ReVelle, et. al., 1969)

- Nonlinear Optimization Model for Screening Multipurpose Reservoir Systems (Sinha, Rao, and Bischof, 1999)

2.3.4 Basin Operations

- Simulation/Optimization Modeling for Water Resources Management (Belaineh, Peralta, and Hughes, 1999)
- Hierarchical Analyses of Water Resources Systems, Modeling and Optimization of Large-Scale Systems (Haimes, 1977)
- Comparison of Stochastic and Deterministic Dynamic Programming for Reservoir Operating Rule Generation (Karamouz and Houck, 1987)
- Linear Programming Models for Water Pollution Control (Loucks, Revelle, and Lynn, 1967)
- Optimal Deterministic Reservoir Operations in Continuous Time (Morel-Seytoux, 1999)
- Limitations of Deterministic Optimization Applied to Reservoir Operations (Philbrick and Kitanidis, 1999)
- Stochastic Optimal and Suboptimal Control of Irrigation Canals (Reddy and Jacquot, 1999)

2.3.5 Municipal Planning

- Guidelines for Implementing an Effective Integrated Resource Planning Process (Albani, 1997)
- Guidelines for the Preparation of Planning Documents for Developing Community Water Systems Projects (Burton, Sheridan, and Marko, 2001)
- Integrated Water Resources Management: Governance, Best Practice, and Research Challenges (Hooper, 2006)
- Decision Support System for Sustainable Water Supply (Huber-Lee et. al., 2006)
- Incorporating Climate Change Information in Water Utility Planning: A Collaborative, Decision Analytic Approach (2010)
- Integrated Water Resources Management (IWRM) and Water Efficiency Plans by 2005 (Jonch-Clausen, 2004)

- Integrating Conservation Into Water Supply Planning (Maddaus et. al, 1996)

- Decision Process and Trade-Off Analysis Model for Supply Rotation and Planning (Nero and Adams, 2006)

- Developing and Implementing a TWM Strategy - Approaches and Examples (Patwardhan et. al., 2007)

- Multiple criteria water supply planning (Rajabi et. al, 1997)

- Application of Knowledge Management to Utilities (Rosen, Frey, Stevens, Miller, Sobrinho, Ergul and Pinkstaff, 2003)

- Drought and Growth Considerations in Long Range Municipal Water Resource Planning (Rossi, 2006)

- Protocol for Developing Water Reuse Criteria With Reference to Drinking Water Supplies (Warner, 2007)

- Water Resources Planning: Manual of Water Supply Practices - M50, Second Edition (2007)

- Managing Constraints to Water Source Development (Wubbena and Hathhorn, 1999)

2.3.6 Municipal Design

- Optimization of Regional Storm-Water Management Systems (Behera, Papa, and Adams, 1999)

- Prioritizing Water Main Replacement and Rehabilitation (Deb, Grablutz, Hasit and Snyder, 2002)

- Decision Support System for Distribution System Piping Renewal (Deb, Hasit, Schoser, and Snyder, 2002)

- A Benders Decomposition Model For Sewer Rehabilitation Planning for Infiltration and Inflow Planning (deMonsabert and Thornton, 1997)

- An Integer Program for Optimizing Sanitary Sewer Rehabilitation Over a Planning Horizon (deMonsabert, Ong, and Thornton, 1999)

- Artificial Intelligence Helps JEA Optimize Water Resources (Eaton and Barker, 2006)

- Optimizing a Water Master Plan (Frey et. al, 2001)
- Ant Colony Optimisation for Design of Water Distribution Systems (Maier, 2003)
- Using Genetic Algorithms to Rehabilitate Distribution Systems (Wu, Boulos, Orr, and Ro, 2001)
- Reliability-Based Optimal Design of Water Distribution Networks (Xu and Goulter, 1999)

2.3.7 Municipal Operations

- Water Quality Modeling in Distribution Networks (Elton, Brammer, and Tansley, 1995)
- Implementing a Prototype Energy and Water Quality Management System (Jentgen, 2003)
- Optimizing Operations at JEA's Water System (Jentgen, 2005)
- Optimizing System Operations (Jentgen, Conrad, and Lee, 2005)
- Autocalibration of a Water Distribution Model for Water Quality Parameters Using GA (Munavalli and Kumar, 2006)
- Optimal Control of Water-Supply Pumping Systems (Ormsbee and Lansey, 1994)
- Drought Management of Existing Water Supply System (Randall, Houck, and Wright, 1990)
- Artificial Intelligence Systems for Water Treatment Plant Optimization (Stanley, 2001)

3 RESEARCH APPROACH

3.1 Hypothesis and Research Questions

The hypothesis for this research is that an integrated water resources plan can achieve balance between the three components of sustainability (economic/financial, social, and environmental). The burning question for this research to answer is: ***"Can a municipal utility, which is tasked with the implementation of high level policy directives and saddled with constraints, develop an integrated water resources plan without a overriding bias towards the economic/financial component at the expense of the social and environmental components?"*** In answering this question, the research has focused on the use of goal programming to incorporate social and environmental sustainability factors into municipal integrated water supply planning. The following subsidiary research questions below will be answered in the context of this framework.

1. ***Can the three primary components of sustainability be equally weighted and still yield feasible solutions?*** Historically, municipal water utilities either explicitly or inherently apply a greater weight to the financial aspect of sustainability. Perhaps this conventional approach simply demonstrates that a balanced approach is infeasible.

2. ***What data are needed by the decision makers in order to successfully analyze social and environmental components?*** Financial data is readily available to the decision

makers: budgets, rates, debt service, etc. The social and environmental data may be more difficult to obtain. The availability of financial data and the comfort in dealing with their easily quantifiable nature is the overwhelming reason why water supply plans generally resort to financial economics as the primary basis for decision making.

3. ***How can the inherently qualitative aspects of environmental impact be quantified?*** Measures such as area of habitat for local wildlife, volume of runoff, and carbon footprint may be considered.

4. ***How can the inherently qualitative aspects of social impact be quantified?*** Measures such as impact of activities on areas of lower income and affordability will be considered as potential social goals.

5. ***Can optimization techniques, which are prevalent in facility and network design and inter-basin planning, be implemented at the municipal planning level?*** The literature review demonstrates that optimization techniques are used in the water industry, but not at the municipal planning level.

6. ***Can generic goals be set up to minimize the need for subjective weighting?*** In order to minimize subjectivity, the each goal value will be normalized. As the research progresses, the areas that require subjectivity will be identified.

3.2 Research Context

With the Triple Bottom Line of Sustainability, integrated water resources planning efforts must analyze alternatives to address the potentially conflicting goals of economics (financial), environmental, and social issues. Goal programming is a technique which uses optimization methods to provide a means to solve a problem by striving towards multiple objectives simultaneously. Bammi and Bammi (1979) used a similar technique to develop a comprehensive land use plan. This research will seek to apply a similar optimization framework to water supply. To accomplish this, the following high-level tasks must be undertaken:

1. Define Requirements for the IWRP
2. Select a goal programming technique for deterministic analysis
3. Define a set of goals consistent with the TBL framework
4. Define a set of alternatives (both supply-side and demand-side) to be used in developing constraints
5. Demonstrate feasibility with a case study of real municipal water utility data

Figure 7 demonstrates how the research approach addresses the tasks identified in the AWWA IWRP process defined in the Water Supply Planning manual of practice (Water Resources Planning, 2007). The following sections discuss each of the seven components to the research.

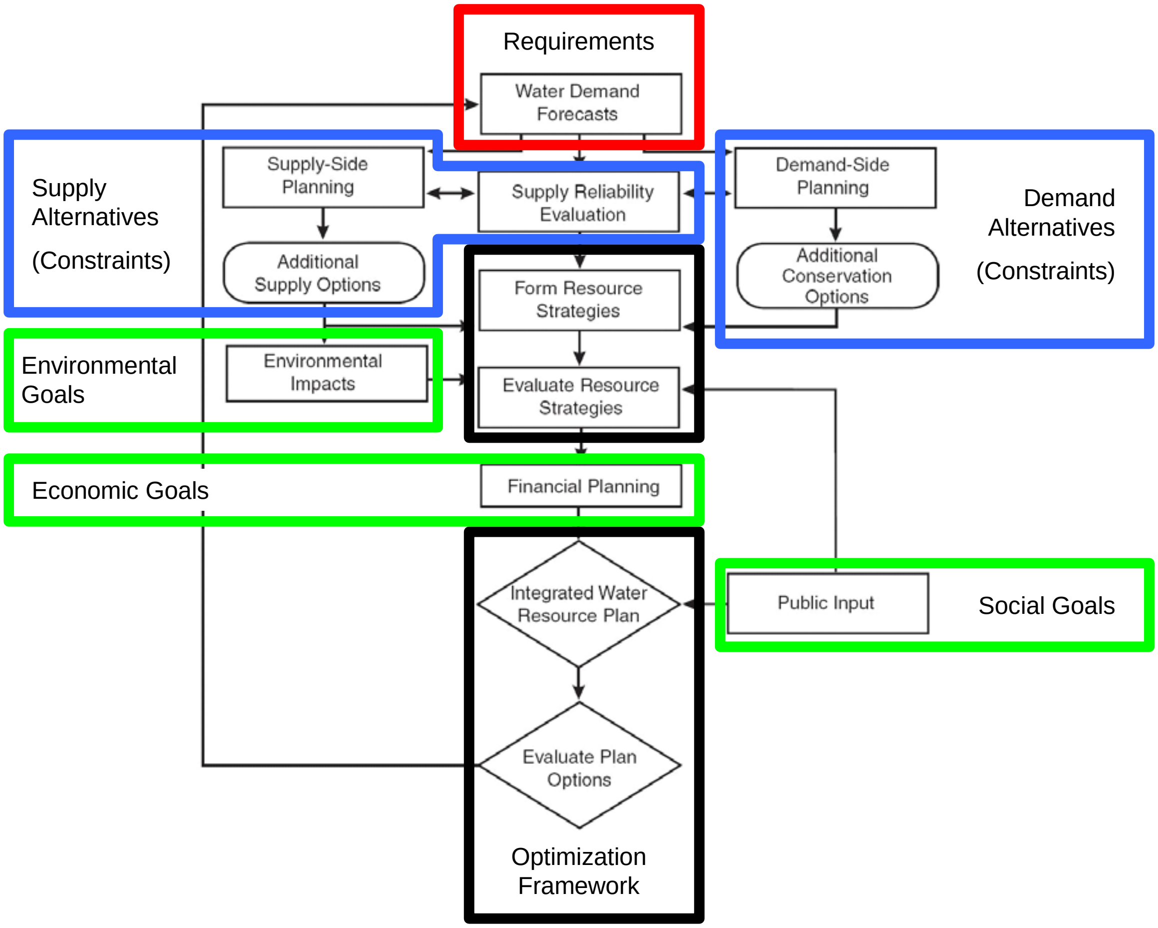

Figure 7: Research Coverage of AWWA Recommended IWRP Process

3.3 Requirements

A general framework will be developed to incorporate three external variables which define the primary requirement for an IWRP effort – how much water is needed to be used by customers:

- **Planning Horizon** – The planning horizon defines the length of the plan, which impacts lifecycle cost calculations, capital improvement scheduling, and the extent of exposure to uncertainty in both climate and economic factors.

- **Demand Forecast –** The demand forecast sets will be segmented by usage type (agricultural, industrial, commercial, residential, governmental, recreational). AWWA recommends four scenarios (normal, dry-year, critical dry-year, and wet year) (Water Resources Planning, 2007). The deterministic model will use one of the scenarios, while the rest will be used to develop the stochastic form of the model
- **Climate Impact –** Weather variations are explicitly categorized in the demand forecast. However, climate change expands those impacts to encompass other factors including water quality. For example, rising sea level may make currently fresh water supplies turn brackish.

3.4 Goal Programming Techniques

As shown in the literature review, little evidence exists of optimization techniques in use at the planning level for municipalities. Using traditional linear programming (optimizing a single objective function subject to a set of constraints) would appear to be an enhancement to the municipal water resources planning arena. However, the very nature of IWRP mandates a multi-objective approach to problem solving. Goal programming is an extension of linear programming to handle multiple objectives. Each goal is given a target value and auxiliary variables are introduced to account for the deviation from the target (both positively and negatively, as needed). The objective function from linear programming is replaced by an achievement function, based on minimizing the deviations from the goals.

3.4.1 Achievement Function

There are three primary means of developing the achievement function under goal programming:

- **Preemptive** (lexicographic) – Each goal is ordered into a priority level, with each level being substantially higher than the next
- **Non-preemptive** (weighted) **–** Each goal is given a relative weight. Goal achievement is normalized (i.e., percentage of goal achievement to target) to facilitate direct comparison
- **Minmax** (balanced) **–** The achievement function seeks to minimize the maximum unwanted deviation, or, alternatively, to maximize the minimum progress towards all objectives

The research will focus on a balanced achievement function and preemptive methods in order to lessen the impact of subjective weighting, which would be better addressed through means such as analytical hierarchy process. The research approach will focus on existing documented best practices and industry standards to develop the general achievement functions. However, variables will be identified that may be addressed through further research at a specific application (for example, obtaining values for weights from decision makers at a specific municipal utility).

3.4.1.1 False start

The starting point for the development of a generic achievement function was originally to have been a hybrid approach between the preemptive and balanced methods, beginning with the assumption that economic goals, being the easiest to quantify and understand for most decision makers, will have the highest priority under the preemptive approach. Therefore, the economic goal portion of the TBL would have been entered as a constraint. The resulting problem would have then addressed the social and economic goals through the balanced approach.

However, the hybrid approach as originally envisioned would have merely replicated the same inherent bias that a water utility decision-maker might have towards financial goals, defeating the intended purpose of elevating environmental and social concerns to the same level as financial concerns. Therefore, a balanced approach, equally weighting all three components, will be used in this research.

3.4.1.2 Balanced Approach

The goal objectives may be expressed as follows:

$$Z_{Economics} = \sum_{j=1}^{n} c_{jEconomics} x_j \qquad (1)$$

$$Z_{Environmental} = \sum_{j=1}^{n} c_{jEnvironmental} x_j \qquad (2)$$

$$Z_{Social} = \sum_{j=1}^{n} c_{jSocial} x_j \qquad (3)$$

Where $\mathbf{x_1, x_2, \ldots, x_n}$ are decision variables, $\mathbf{c_1, c_2, \ldots, c_n}$ are contribution coefficients that represent the marginal contribution of the decision variable to the Economic, Environmental, and Social goals, and $\boldsymbol{n}$ is the number of alternatives (decision variables). The preliminary achievement function will be as follows:

$$\text{Maximize} \quad Z = z \qquad (4)$$

Subject to:

$$z \le \frac{\sum_{j=1}^{n} c_{jEconomics} x_j}{G_{Economics}} \quad \text{Economic goal achievement} \tag{5}$$

$$z \le \frac{\sum_{j=1}^{n} c_{jEnvironmental} x_j}{G_{Environmental}} \quad \text{Environmental goal achievement} \tag{6}$$

$$z \le \frac{\sum_{j=1}^{n} c_{jSocial} x_j}{G_{Social}} \quad \text{Social goal achievement} \tag{7}$$

$$\sum_{j=1}^{n} a_{ij} x_j \le b_i \text{, for i=1,…, } m \quad \text{Other constraints (supply, demand, budget, etc.)} \tag{8}$$

Where $\boldsymbol{z}$ is the deviation variable for the goal achievement, $\mathbf{G_k}$ is the maximum goal achievement threshold for $\mathbf{k} \in$ {Economic, Environmental, and Social}, $\mathbf{a_{ij}}$ are technological coefficients that represent the unit usage by $\mathbf{x_j}$ of the right-hand side coefficient $\mathbf{b_i}$, and $\boldsymbol{m}$ is the number of constraints such as supply, demand, and budget.

The aforementioned framework shows directly related impacts on goal achievement. For example, an alternative may specify a length of pipe, which has a defined cost if chosen and therefore cost impact is directly related to the choice of that alternative. In addition to these directly related impacts, there will be indirect contribution to goals from the cumulative effect of the selected set of alternatives. These cumulative effects are expected to be non-linear.

For example, in calculating the affordability (social indicator) impact, the cumulative impacts of all of the selected alternatives are calculated and then the affordability index would be determined: expected median cost per household (anticipated rates multiplied by anticipated usage, after taking into account all demand and supply alternatives) divided by median household income. These impacts will be developed and documented as the research develops.

3.5 Goal Determination

The next step in the research is to develop a framework to address goals that are consistent with the three factors of the triple bottom line. Inputs from industry standards (Huber-Lee et. al, 2006; Water Resources Planning, 2007) are be used to help define a general form of the goals consistent with the sources of data expected to be available to a utility.

The first component of the triple bottom line (TBL) is Economics. Economic goals, as defined by the TBL, are financial in nature, and are, therefore, the most used traditionally. These goals may include keeping costs [Capital, Operations & Maintenance (O&M), or lifecycle] within a set budget. Another goal may be to have a minimal increase in revenue requirements for the utility, therefore, making low increases in customer rates. A discount rate will be accommodated due to the potential need to evaluate bond financing or to calculate the lifecycle cost.

The second component of the TBL is the Environment. Environmental goals will focus on three categories: human, biological, and physical. Human resources concern issues that affect the human environment including land use and public services. Biological resources include flora and fauna that are impacted (fish, birds, wildlife, and plant life). Physical resources include wetlands, soils, and air quality (Water Resources

Planning, 2007). As these three categories are interrelated, a single generic goal (or set of goals) for the environment will be developed.

The third goal category of the TBL is Social Impacts. These goals may manifest themselves through a number of means that vary widely by location. Some social impacts may include:

- Affordability of water and wastewater rates
- Historic and cultural impacts of site locations
- Socioeconomic impact (equity and fairness) of location of treatment and ancillary facilities
- Job creation an retention from economic development

A set of generic goals will be developed to encompass all three components of the TBL as feasible, as determined by the information expected to be available to a municipal utility. Examples of potential generic goals for each of the three sustainability components are described below. While a number of general goals may be developed for each category, for demonstration purposes, one potential goal is presented for each category.

3.5.1 Economic Goal Development

The most easily understood set of goals will be those related to the economic (financial) goals, as they relate to well documented issues such as budgets and rates. Compliance with capital and O&M budgets may be thought of as constraints, although if they limit the feasible space, these issues could be converted to goals, as creative financing can often be used to effectively modify the budgets. For example, debt ceiling could be raised or revolving loan funds could be used to expand capital budget. Outsourcing or internal efficiency improvements (both personnel and operational improvements such as energy efficiency or plant optimization) can be used to decrease the O&M baseline, thus expanding the available O&M budget.

If we leave budget compliance as a constraint type, an example of an economic goal would be to have the expected water rate increase to be less than 10 percent. From a public relations perspective, utilities always want to keep their rates low. When increases are required, utility management generally want to keep the rate increase low. While preferably lower than the CPI, sometimes a rate increase to meet new demands or regulations must be higher. A rate increase of single digits is easier for the utility's public relations than a double digit rate increase. The goal shortfall for an economic factor is shown by the following equation:

$$Z_{Economic} = \frac{\left(\frac{r'_{Water} - r_{Water}}{r_{Water}} - 1 \right) - G_{Economic}}{G_{Economic}} \tag{9}$$

Where, $\boldsymbol{r_{Water}}$ is the existing water rate, $\boldsymbol{r'_{Water}}$ is the expected water rate required to meet revenue requirements of the selected combination of alternatives, and $\boldsymbol{G_{Economic}}$ is the threshold or target for the rate increase goal (in this case not more than 9.9%).

3.5.2 Environmental Goal Development

As mentioned above, environmental goals can encompass human, biological and physical environment. For example, wastewater disposal through the use of artificial wetlands can provide wildlife habitat. Thus, a relevant goal might be area of wetland restored. While this measure doesn't directly count the birds and other wildlife that will live there, the area serves as a proxy for the environmental health. Another example would be to reduce the impact of surface water (rivers and lakes) and groundwater (wells) withdrawals through the use of alternative sources (wastewater reuse, aquifer storage and recovery, etc.). This reduction in withdrawals will provide more water in the watershed for fish and wildlife. A general environmental goal might be to have net increase in surface water and groundwater withdrawals of 0. That is, any demand increases above current levels to be met, or offset, by alternative sources. Therefore an example the equations quantifying a goal shortfall for an environmental factor is as follows:

$$P_{\mathrm{TOT}} = P_{\mathrm{GW}} + P_{\mathrm{SW}} + P_{\mathrm{AS}} \tag{10}$$

$$Z_{Environmental} = \frac{P'_{GW} + P'_{SW}}{P_{GW} + P_{SW}} - G_{Environmental} \tag{11}$$

Where, $\boldsymbol{P_{TOT}}$ is the total water production, $\boldsymbol{P_{GW}}$ is the volume of ground water pumpage, $\boldsymbol{P_{SW}}$ is the volume of surface water withdrawals, $\boldsymbol{P_{AS}}$ is the volume of water production from alternate sources. $\boldsymbol{P'_{GW}}$ is the volume of ground water pumpage after implementing planned set of alternatives, $\boldsymbol{P'_{SW}}$ is the volume of surface water withdrawals after implementing planned set of alternatives, and $\boldsymbol{G_{Environmental}}$ is the threshold or target for the ratio of future withdrawals to existing withdrawals (in this case, not more than 100%, to account for zero growth in withdrawals).

3.5.3 Social Goal Development

One way to incorporate a social goal into the model is through the use of an affordability metric. The industry guideline is that water service is affordable if the water bill for a household is less than two percent of household income. With surveys and statistical analysis, studies can be conducted to determine the relationship between consumption profile and income distribution and obtain a calculated affordability distribution. The most common way to obtain the affordability index without the cost of a survey and study is to use the median customer usage multiplied by the water rate and divide by the median household income in the utility's service area. Based on the assumption that a low-income user will have a lower water use (no pools or irrigation or other high volume discretionary usage), this calculation provides a good overall measure of affordability.

To incorporate this measure into the model, three pieces of information must be determined: the water rate required after the implementation of the selected alternatives, the expected water usage after any demand management techniques implemented, and the median household income for the service area. The affordability goal will then be normalized against the 2% target threshold. The goal shortfall for affordability can be given by the following equation:

$$Z_{Affordability} = \frac{\dfrac{C_{Water} r'_{Water}}{I_{HH}} - G_{Affordability}}{G_{Affordability}} \qquad (12)$$

Where, $\boldsymbol{C}_{Water}$ is average water consumption after implementation of selected combination of alternatives, $\boldsymbol{r'}_{Water}$ is the expected water rate required to meet revenue requirements of the selected combination, $\boldsymbol{I}_{HH}$ is the median household income for the utility's service area, and $\boldsymbol{G}_{Affordability}$ is the threshold or target for the affordability goal (in this case not more than 2% of household income).

3.6 Development of Alternatives

Given the requirements and goals, the next step is to determine the range of feasible options available to the decision maker. In this effort, a general set of alternatives will be developed for both supply side and demand side approaches. Each alternative will have defined attributes which will be used in developing the constraints.

3.6.1 Supply-side Management

Supply alternatives will include the existing supplies, new or enhanced surface water supplies, new or enhanced ground water supplies and alternative sources of supply. Alternative sources of supply may include wastewater reuse/recycling, aquifer storage and recovery, and stormwater reuse, among other options. Each supply alternative will have attributes defined to help define the goal achievement and constraints. These attributes may include:

- Capital Costs
- Operating and Maintenance (O&M) Costs
- Capacity
- Reliability

- Expected Life
- Safe Yield
- Impact on environmental and social goals (capital and O&M costs will address the economic goal achievement)

3.6.1.1 Example of Supply Source

Examples of source of supply to meet demands might include upgrade to an existing water treatment plant or construction of a new one. To demonstrate the data needed to quantify the impacts on the goals and constraints, a new desalinization plant will be used. The facility information contained in Table 3 below and numbers used are merely notional and not indicative of real world conditions.

Table 3. Sample Source of Supply Alternative

Facility Description	Reverse Osmosis Desalinization Plant
Capacity	20 MGD
Capital Cost	$100 million
O&M costs (per year)	$5 million
Expected usable lifetime	30 years
Reliability of source of supply	100% - Brackish groundwater replenished by Atlantic Ocean means no potential shortage of raw water, as opposed to potential low flows on current river source
Environmental Impacts	• No surface water withdrawals (positive) • Increase power usage as RO is energy intensive (negative) • Waste brine injected into brackish aquifer (neutral) • After construction, no impacts to wildlife (neutral)
Social Impacts	• More costly than surface water withdrawal and treatment (affordability negative impact) • Siting of plant a concern (aesthetic impacts if near beach, social concerns if sited in low-income area) • Creation of living wage jobs (positive)

3.7 Defining Goals

The first step in developing the general model for goal programming for sustainability is to define the performance measures that aggregate into the goals. Each of the three goals (Economic, Environmental, and Social) may be a composite of multiple performance measures related to the specific aspect of the TBL. In order to be useful for decision analysis, and particularly in mathematical modeling such as goal programming, the metrics must be quantitative and clearly defined.

The metrics need to be numeric, or able to be easily converted to a numeric value (categorical variables, for example) for use in the mathematical model. While the measures do not need to be linear or continuous, they should be able to designate best case, or target, and worst case for determining direction of goal achievement (Is a larger number better, or is lower better). These requirements will be needed for normalization of each measure and aggregation of the measures into a consolidated goal for each of the TBL aspects.

Just as important as quantitative nature of the measures, clear definition of the metrics is also crucial. The measures must unambiguous. For example, a measure of "amount of water from a renewable resource" can lead to analysis of the wrong problem. Is the measure focusing on surface water, groundwater or both? What is the definition of "renewable"?

The next three chapters will discuss the definition of economic, environmental, and social performance measures that may be used to create the goal constraints in the goal programming model.

4 ECONOMIC SUSTAINABILITY MEASURES

Because other branches of economics such as welfare economics and environmental economics are covered in the environmental and social aspects of sustainability, economic sustainability measures should more accurately be titled "financial" measures, as they deal with dollars. In order to come up with a set of potential measures from which to create a goal for the economic aspect of sustainability in the GP model, the American Water Works Association Research Foundation's guidelines for TBL reporting (Kenway, Howe, and Maheepala, 2007) were reviewed and supplemented by insight from the System of Environmental-Economic Accounting for Water (SEEAW) from the United Nations Statistics Division (2007). As the guidelines for TBL reporting are meant for reporting, some of the measures may be better suited for reporting progress than used directly for decision making. The relevant measures are discussed below.

- **Customer Payments -** (TBL Guidance measure C1) – this category of measure encompasses operating revenue by customer class. Depending on the organization, operating revenues may include water sales, wastewater fees, reclaimed water sales, stormwater fees, impact fees, miscellaneous fees, or a combination of the types. Customer classes may include residential, commercial, industrial, agricultural and governmental. With the large variety of combinations of revenue stream and customer class, this measure may be useful for decision making when defined by the utility. For example, a utility looking to limit the burden on residents by adding additional fees to commercial customers will define measures differently than an organization looking to spur business development by keeping commercial and industrial rates lower.

- **Operations & Maintenance (O&M) Costs per unit volume** - (TBL Guidance measure C4) – this category of measure focuses on O&M costs (typically labor, chemicals, materials, and energy). By looking at the unit costs per volume (ccf, AF, kgal, etc.), the relative efficiency of the treatment and distribution processes can be assessed.
- **Payroll** - (TBL Guidance measure C7) – describes the amount of money paid to the local economy through wages. This is an important measure when expansion creates new jobs in the community, and the marginal payroll increase could actually be a social benefit. However, in a static situation where no more jobs will be produced by the new water supply alternative, the measure is better suited to reporting than decision making.
- **Interest on debt + Dividend Payments** - (TBL Guidance measure C8) – Debt management is important to any operations. Interest on debt reflects the result of the bond interest rate, which is a reflection of the management and stability of the utility. Another way this is presented is Interest costs as a percentage of total expenses. Dividend payments might be made to a municipality’s general fund.

Thus, if the measure of interest on debt and dividend payments are considered together, the lower the amount is generally better from the utility point of view. However, a municipality may want to increase the dividend payments from the utility in order to bolster the general fund with no impact on the tax rates. This potential incongruity where a utility may want to drive interest cost down while increasing dividend payments make the combined measure unsuitable for a generic measure for decision making, especially when other debt related measures are available.

- **Debt Ratio** - (TBL Guidance measure C9) – can be expressed as total outstanding debt as a percentage of a regulatory debt ceiling, as Debt/Equity from the utility's balance sheet, or as a coverage ratio (Net Income divided by debt service payment). A debt ceiling may be regulated and the coverage ratio is generally part of the bond covenant when utilities issue revenue bonds. One of these measures could be useful in decision making when borrowing to fund capital projects is a major component.
- **Return on Assets** - (TBL Guidance measure C10) – is defined as Net Income divided by total assets. Given the high value of assets, especially buried assets, that a utility has relative to the desire to keep water rates low, ROA tends to be lower at municipalities than in the private sector. Also, with the large volume of long term assets (for example, distribution pipes with 50 year lifetimes), any changes in water supply alternatives may have a negligible effect on ROA.
- **Total Taxes Paid** - (TBL Guidance measure C12) – Similar to the dividend issue

discussed above, increases in taxes paid are negative from a utility's net income, but positive when viewed from the municipality's general fund.

- **Subsidies Received** - (TBL Guidance measure C13) – the inverse of the taxes paid measure. Increases in subsidies aid the utility bottom line, but hurt the municipality's balance. In addition, the AWWA Manual of Practice (Water Supply Planning Manual, 2007), the Millennium Development Goals (2005), and the System of Environmental-Economic Accounting for Water (SEEAW) (2007) all focus on self sufficiency for utilities.
- **Asset Renewal** - (TBL Guidance measure D1) – focuses on the replacement of older assets with newer, more efficient assets. Since pipes are generally the largest asset class, this measure is probably better used for an asset management program or reporting than for water supply planning.
- **Operating Ratio** – is defined as operating costs (O&M plus debt service) divided by revenues. A value of less than 1.0 implies self sufficiency and a positive net income. (SEEAW, 2007)

After reviewing these measures, the following measures were identified to form the general list, or menu, of economic indicators:

- **Annualized Cost of Water Supply Alternative** – In order to address both O&M and capital costs, the annualized cost of an alternative is used. Generally, this measure by itself can serve as the Goal for the GP. The value of this measure is the sum of the

- Amortized capital costs over the expected life of the asset,
- The fixed O&M costs, and
- The variable O&M costs multiplied by the volume of water supplied by the alternative.

- **Net Income –** a key factor related to a number of the TBL classes of measures including Return on Assets, Customer Payments, Operating Ratio, and Debt Ratio.
- **Operating Ratio –** a different manner of expressing net income
- **Average Water Rate –** Customer payments as tailored by the utility as to which type(s) of customers to be evaluated. Calculation is Total water sales in customer class divided by the total volume of water sold to the customer class.

5 ENVIRONMENTAL SUSTAINABILITY MEASURES

In order to come up with a set of potential measures from which to create a goal for the environmental aspect of sustainability in the GP model, the American Water Works Association Research Foundation's guidelines for TBL reporting (Kenway, Howe, and Maheepala, 2007) were reviewed and supplemented by insight from the System of Environmental-Economic Accounting for Water (SEEAW) from the United Nations Statistics Division (2007), the Environmental Performance Index (2008), and the Global Reporting Initiatives Sustainability Reporting Guidelines (2006). As with the economic measures, some of the measures from the TBL reporting guidelines may be better suited for reporting progress than used directly for decision making. The relevant measures are discussed below.

5.1 Renewable Water Sources

The essential environmental factor is the sustainability of the water sources themselves. If a water source is being used up faster than it is being replenished, then the source is, by definition, unsustainable. In AWWARF (TBL Guidance measure A3), ISEW, and EPI, this class of measure is given great importance. AWWARF recommends the measures of 1) the percentage of groundwater, and 2) the percentage of surface water that come from a renewable source. ISEW has related measures that include the depth of the groundwater table to address the depletion (quantity) of resources. SEEAW has a renewable water source index DIA/Q, which is the domestic, industrial and agricultural usage divided by the quantity of renewable water available (2007).

The EPI water stress indicator is the “percentage of a country’s territory affected by oversubscription of water resources.” Water stress is considered when the water use is more than 40 percent of available supply from renewable sources (EPI, 2008). Water stress can be alleviated to some degree through inter-basin transfers, water reuse and desalination.

Agriculture is by far the largest user of freshwater from streams, lakes, and groundwater aquifers, with irrigation accounting for 70% of freshwater extraction globally and as much as 80-90% in some developing countries (EPI, 2008). Since agricultural use accounts for such a large percentage of water usage, the percentage of water withdrawn by agriculture from renewable sources is identified as a separate measure in ISEW. EPI also includes a separate measure for Irrigation Water Stress. When water is abstracted for irrigation in water stressed areas (catchments in which consumption exceeds 40 percent of renewable water supplies) it can contribute to excessive concentration of non-point source pollution from agricultural runoff, in addition to impacting seasonal flows from surface water sources.

In addition to the quantity issues related to renewable water sources, quantity is also a concern related to the degradation of the source. ISEW specifies a quality measure of the salinity of the groundwater. EPI has the Water Quality Index, or WATQI (2008). WATQI is composite indicator for five parameters, with the following targets:

- Dissolved Oxygen (DO) of 6 mg/L for "warm waters" (>20C) and 9.5 mg/L for "cold waters" (<20C);
- Electrical Conductivity(EC) of 500 micro-Siemens/cm
- pH of 6.5-9.0
- Total Phosphorus (P) of 0.05 mg/L, or 0.025 mg/L of Ortho Phosphate
- Total Nitrogen (N) of 1 mg/L, or 0.5 mg/L Dissolved inorganic Nitrogen or Nitrate+Nitrite, or 0.05 mg/L Ammonia

Water Recycling - (TBL Guidance measure A2) or wastewater reuse, provides an enhanced impact as recycling reduces both the withdrawals from raw water sources and the discharges to receiving bodies. This fact makes water recycling a key measure for environmental sustainability.

While renewable sources are at central to the environmental sustainability problem, the term "renewable" is exceedingly hard to define, as acknowledged by the literature. Other than ocean desalination (at least in terms of quantity of water available), virtually every other source of water must be evaluated in depth to determine how renewable the source is. Therefore, the measures for inclusion in the generic menu include percentage of total water withdrawals from renewable sources and percentage of total water usage from water recycling or reuse.

5.2 Other Environmental Sustainability Indicators

After addressing the largest environmental issue (renewable water sources), other environmental factors must be reviewed. The measures include the following:

- **Total Water Use** - (TBL Guidance measure A1) **–** this category of measure encompasses consumption in total and in average by customer class. Customer classes may include residential, commercial, industrial, agricultural and governmental. The usage may be total water withdrawals, total water sales volume, total volume of wastewater discharged, average water usage by customer class, and average wastewater collection by customer class. A number of these indicators are useful in developing both demand forecasts and the impact of demand management or conservation programs at the utility.

- **Impact of Withdrawals** - (TBL Guidance measure A4) **–** The watershed ecosystems can be affected with respect to quantity and quality by withdrawals. AWWARF leaves the definition of this class of measurement ambiguous, defining the measure as the impact of the utility on wetlands listed on the Ramsar List of Wetlands of International Importance and other affected ecosystems.

- **Significant Discharges by Type** - (TBL Guidance measure A5) **–** This AWWARF measure focuses more on untreated discharges as opposed to treated wastewater discharge into a receiving body. The three measures that AWWAF recommends are 1) trade waste collected, 2) trade waste compliance percentage, and 3) number of sewage overflows. The trade waste measures focus on the potential impact of industrial pollutants on the environment. While the number, and volume, of sewage overflows attempt to address the potential pollutant loading to a receiving body from untreated sewage. These measures might be useful in decision making in alternative water source selection, but are probably better left as reporting focused measures.

- **Energy Usage** – (TBL Guidance measure A6) – Energy usage has many impacts from the production and consumption. The basic measures of kWh used per volume of water or wastewater are the starting points. Energy costs per volume of water or wastewater are the next level of measures. These measures, plus the percentage of energy used from renewable sources (solar, wind, hydro, geothermal, tidal), are measures that can be used in decision making.

- **Total Waste** – (TBL Guidance measure A8) – Analogous to the WATQI for water, receiving body water quality is the focus for this measure to determine the impact of wastewater. AWWARF's high level measures are percentage of wastewater that is treated to a primary level, to secondary standards, and to tertiary treatment levels. An alternative to the percentages is the total mass of nutrient load discharged by Biochemical Oxygen Demand (BOD), Suspended solids (SS), Nitrogen (N), and Phosphorus (P).

- **Impact of Discharges** - (TBL Guidance measure A9) – The watershed ecosystems can be affected with respect to quantity and quality by discharges. The first measure is the volume of water discharged wetlands listed on the Ramsar List of Wetlands of International Importance. As with the withdrawal measures, AWWARF leaves the definition of this class of measurement ambiguous, by defining it as "overall contribution to environmental trends." This may be due to the fact than in some cases, the treated wastewater discharges improve the quality of the receiving body.

- **Biodiversity Rich Habitats** - (TBL Guidance measure A10) – The area of land managed that provides a habitat encouraging biodiversity is the measure specified by both AWWARF and the Global Reporting Initiative. This measure is not likely to be used in the decision to select an alternative water source, with the exception of when a new source (dam for a reservoir, for example) will reduce the habitat.

- **River Quality** – (TBL Guidance measure A15) – Similar to the Total Waste indicator, AWWARF focuses on the river quality as related to both withdrawals and discharges. The measures defined are flow, nutrients, and sediment loads.

- **Greenhouse Gas (GHG) Emissions –** (TBL Guidance measure A7) **–** In keeping with the Kyoto protocol, AWWARF recommends reporting on the carbon footprint, including the identified GHGs: Carbon Dioxide (CO2), Methane (CH4), Hydrofluorocarbons (HFC), PFC, and CO2 equivalents. In addition, indirect emissions from energy consumption from suppliers (electric utility, steam generation, etc. – as listed in TBL Guidance measures A11 and A12) and the emissions from utility vehicles. While a worthwhile measure, energy usage and percent of energy from a renewable source capture much of the focus for the greenhouse gas emissions measure at a simpler calculation. However, if a utility wanted to estimate the contribution to its carbon footprint from the utility electricity consumption, the factors shown in Table 4 could be used.

Table 4. 1998-2000 Average State-Level Carbon Dioxide Emissions Coefficients for Electric Power (EIA, 2002)

	Carbon Dioxide			Methane	Nitrous Oxide
Region / State	**Lbs / kWh**	**Short tons / MWH**	**Metric tons / MWH**	**Lbs / MWH**	**Lbs / MWH**
New England	**0.98**	**0.491**	**0.446**	**0.0207**	**0.0146**
Connecticut	0.94	0.471	0.427	0.0174	0.0120
Maine	0.85	0.426	0.386	0.0565	0.0270
Massachusetts	1.28	0.639	0.579	0.0174	0.0159
New Hampshire	0.68	0.341	0.310	0.0172	0.0141
Rhode Island	1.05	0.526	0.477	0.0068	0.0047
Vermont	0.03	0.014	0.013	0.0096	0.0039
Mid Atlantic	**1.04**	**0.52**	**0.471**	**0.0093**	**0.0145**
New Jersey	0.71	0.353	0.320	0.0077	0.0079
New York	0.86	0.429	0.389	0.0081	0.0089
Pennsylvania	1.26	0.632	0.574	0.0107	0.0203
East-North Central	**1.63**	**0.815**	**0.74**	**0.0123**	**0.0257**
Illinois	1.16	0.582	0.528	0.0082	0.0180
Indiana	2.08	1.038	0.942	0.0143	0.0323
Michigan	1.58	0.790	0.717	0.0146	0.0250
Ohio	1.80	0.900	0.817	0.013	0.0288
Wisconsin	1.64	0.821	0.745	0.0138	0.0260
West-North Central	**1.73**	**0.864**	**0.784**	**0.0127**	**0.0269**
Iowa	1.88	0.941	0.854	0.0138	0.0298
Kansas	1.68	0.842	0.764	0.0112	0.0254
Minnesota	1.52	0.762	0.691	0.0157	0.0247
Missouri	1.84	0.920	0.835	0.0126	0.0288
Nebraska	1.40	0.700	0.635	0.0095	0.0219
North Dakota	2.24	1.121	1.017	0.0147	0.0339
South Dakota	0.80	0.399	0.362	0.0053	0.0121
South Atlantic	**1.35**	**0.674**	**0.612**	**0.0127**	**0.0207**
Delaware	1.83	0.915	0.830	0.0123	0.0227
Florida	1.39	0.697	0.632	0.015	0.0180
Georgia	1.37	0.683	0.619	0.0129	0.0226

Region / State	Carbon Dioxide			Methane	Nitrous Oxide
	Lbs / kWh	Short tons / MWH	Metric tons / MWH	Lbs / MWH	Lbs / MWH
Maryland and Washington, DC	1.37	0.683	0.620	0.0118	0.0206
North Carolina	1.24	0.621	0.563	0.0105	0.0203
South Carolina	0.83	0.417	0.378	0.0091	0.0145
Virginia	1.16	0.582	0.528	0.0137	0.0192
West Virginia	1.98	0.988	0.897	0.0137	0.0316
East-South Central	**1.49**	**0.746**	**0.677**	**0.0128**	**0.024**
Alabama	1.31	0.656	0.595	0.0137	0.0223
Kentucky	2.01	1.004	0.911	0.0140	0.0321
Mississippi	1.29	0.647	0.587	0.0132	0.0165
Tennessee	1.30	0.648	0.588	0.0105	0.0212
West-South Central	**1.43**	**0.714**	**0.648**	**0.0087**	**0.0153**
Arkansas	1.29	0.643	0.584	0.0125	0.0203
Louisiana	1.18	0.589	0.534	0.0094	0.0112
Oklahoma	1.72	0.861	0.781	0.011	0.0223
Texas	1.46	0.732	0.664	0.0077	0.0146
Mountain	**1.56**	**0.781**	**0.709**	**0.0108**	**0.0236**
Arizona	1.05	0.525	0.476	0.0068	0.0154
Colorado	1.93	0.963	0.873	0.0127	0.0289
Idaho	0.03	0.014	0.013	0.008	0.0033
Montana	1.43	0.717	0.650	0.0108	0.0227
Nevada	1.52	0.759	0.688	0.0090	0.0195
New Mexico	2.02	1.009	0.915	0.0131	0.0296
Utah	1.93	0.967	0.878	0.0134	0.0308
Wyoming	2.15	1.073	0.973	0.0147	0.0338
Pacific Contiguous	**0.45**	**0.224**	**0.203**	**0.0053**	**0.0037**
California	0.61	0.303	0.275	0.0067	0.0037
Oregon	0.28	0.141	0.127	0.0033	0.0034
Washington	0.25	0.123	0.111	0.0037	0.0040
Pacific Non-Contiguous	**1.56**	**0.780**	**0.707**	**0.0161**	**0.0149**
Alaska	1.38	0.690	0.626	0.0068	0.0089
Hawaii	1.66	0.831	0.754	0.0214	0.0183
United States	***1.34***	***0.668***	***0.606***	***0.0111***	***0.0192***

The measures above were reviewed for the ability to be used to evaluate alternative water supply strategies, as well as for the relative importance shown by the data sources. As such, the following measures were identified to form the general list, or menu, of environmental indicators to be used in the general form to illustrate the potential for incorporating goal programming into total water management:

- **Percentage of Water from Renewable Sources –** core indicator – "renewable" to be defined by location

- **Wastewater Reuse Percentage –** Most straightforward renewable source calculation
- **Total Waste Discharged –** nutrients (P, N, BOD, SS) as defined by local needs
- **Volume of Wastewater Discharged to Receiving Body –** also may be defined as volume of water to aid wetlands, as needed by utility
- **Total Energy Usage and Percentage of Energy from Renewable Sources –** analogs to address Carbon Footprint (GHG Emissions)

6 SOCIAL SUSTAINABILITY MEASURES

Generally, economic goals are well understood and defined, as discussed in Chapter 4. Over the past decade, environmental goals have been developing enhanced understanding and usage. Measures such as carbon footprint, area of wetland restoration and wastewater reuse are in use, as discussed in Chapter 5. The third pillar of sustainability – social – is by far the most difficult to quantify. In the American Water Works Association Research Foundation's guidelines for TBL reporting (Kenway, Howe, and Maheepala, 2007), a number of measures were identified. However, even the authors state that the social measures are lacking. Relevant measures are discussed below.

6.1 General Measures

In an attempt to identify additional measures which may help in goal formulation, the System of Environmental-Economic Accounting for Water (SEEAW) from the United Nations Statistics Division (2007), and the GRI Sustainability Reporting Guidelines (2006) were used to expand the alternatives suggested by AWWARF.

- **Workforce Levels -** (TBL Guidance measure B1) – The number of employees at the utility was the recommended measure. Like Payroll in the Economic measures, this is an internally focused measure and would only be used in aiding water supply alternative decision making if the alternative were providing additional jobs to expand the workforce.

- **Employment** - (TBL Guidance measure B2) – As an expansion of the workforce measure, marginal increase in jobs at the utility would be a benefit. One of the alternative measures in this class was turnover ratio. Employee turnover can be a valuable reporting measure. Too little turnover (less than five percent, for example) can indicate a stagnant workforce, while too much turnover (e.g., twenty percent or more) may signal an unstable work environment. Regardless of what turnover level is, the net gain in jobs is zero on turnover alone, making turnover an ineffective measure for aiding the decision process for water supply alternatives. Two employment related measures are of interest: 1) jobs in the community created related to the water supply project (construction, design, engineering, etc.), and 2) long term jobs created by the additional capacity of water or wastewater treatment (for example, attracting a new factory to the area because of the expanded capacity).

- **OSHA Compliance –** (TBL Guidance measure B3) **–** As a safety measure, days lost due to injury per employee was recommended. This is another inward looking measure that focuses only on the utility and not the community.

- **Affirmative Action –** (TBL Guidance measure B5) **–** As related to employment at the utility, the use of affirmative action as a measure is still inward looking, albeit providing some social benefit to the community. GRI has similar measures, but the focus is on money spent on local suppliers, to strengthen the local economy.

- **Customer Health** – (TBL Guidance measure B6) – AWWARF left this measure ambiguous that, while acknowledging that public health is important, neglected to have a defined measure.

- **Community Involvement** – (TBL Guidance measure B7) –AWWARF, GRI and the MDGs all focus on the community having a say in the direction of the water utility, as water supply is a public health issue. The primary measure that is recommended is the allowance of public comment on major utility initiatives, such as expansion.

- **Customer Satisfaction –** (TBL Guidance measure B8) –Customer Satisfaction is also related to the community involvement, but typically requires a survey to be directly measured, or indirectly calculated through proxy measures such as number of complaint phone calls received by the customer service center.

- **Affordability** – (TBL Guidance measure B10) – Related to economic measures, but focused on the justice aspect of social measures, affordability is typically defined as average water bill per median household income. Alternatives may also include hypothetical water expenses for discretionary use (AWWA uses 6 kgal per month) divided by a poverty level income. Because it is so closely related to economic factors, affordability is generally one of the most straightforward social indicators, and is a key measure in SEEAW, as well.

- **Interruption in Service** – (TBL Guidance measure B11) – This reliability focused measure can be calculated a number of ways, including 1) duration of unplanned interruptions, 2) Sewer collapses per mile of pipe, 3) Water main breaks per mile of pipe, 4) Average time to repair main break (or sewer collapse). All of these are relevant measures with respect to asset management, but may be only ancillary for analysis of supply alternatives.

- **Education and Training –** Public education programs are ubiquitous at water utilities. These programs can range from newsletters mailed with water bill, to advertisements encouraging conservation, to classroom visits by utility staff or field trips to a treatment plant or education center. GRI has identified the number of people reached by educational activities as a useful measure in this category. GRI also recommends a measure of jobs provided to students as a way of using the workforce level to benefit the community.

In addition to the measures discussed above, the AWWA Water Supply Planning: Manual of Practice M50 (2007) addresses additional considerations for planning and analysis that should be considered in the social sustainability indicators: recreational use of water resources, protection of historical and architectural resources, environmental justice, and security.

The recreational use of water sources for fishing, boating, swimming and other water sports, while outside core mission of the utility, helps the utility's image as a provider of public goods. Historical and architectural resources such as battlefields, Native American archeological sites, and other notable architecture are addressed in any Environmental Impact Statement (EIS). The difficulty in defining a metric for this type of measure leads to the use of ordinal or categorical variables for analysis. In Cambria Community Services District's Assessment of Long-Term Water Supply Alternatives (2004), the utility addressed the potential for Native American Indian archaeological sites at one of the potential alternatives through the use of a 1-5 categorical scale in terms of "ease of permitting."

While no formal measures are indicated in the M50 manual, the concepts of **Equity or Environmental Justice** are factors in water resources planning. The placement of a facility or pipe network with respect to socioeconomic status is a key factor. For example, the least expensive location for a facility is generally where property values are low, which is generally where a poorer segment of the population resides. While this is a complicated issue and impacts social, environmental, and economic goals, measures are difficult to create. An example of a successful measure is shown in Figure 8. The data show the health effects (exposure) of air quality by income level.

Unfortunately, calculation of an indicator for this category typically requires a separate study above and beyond analyzing the water source alternatives.

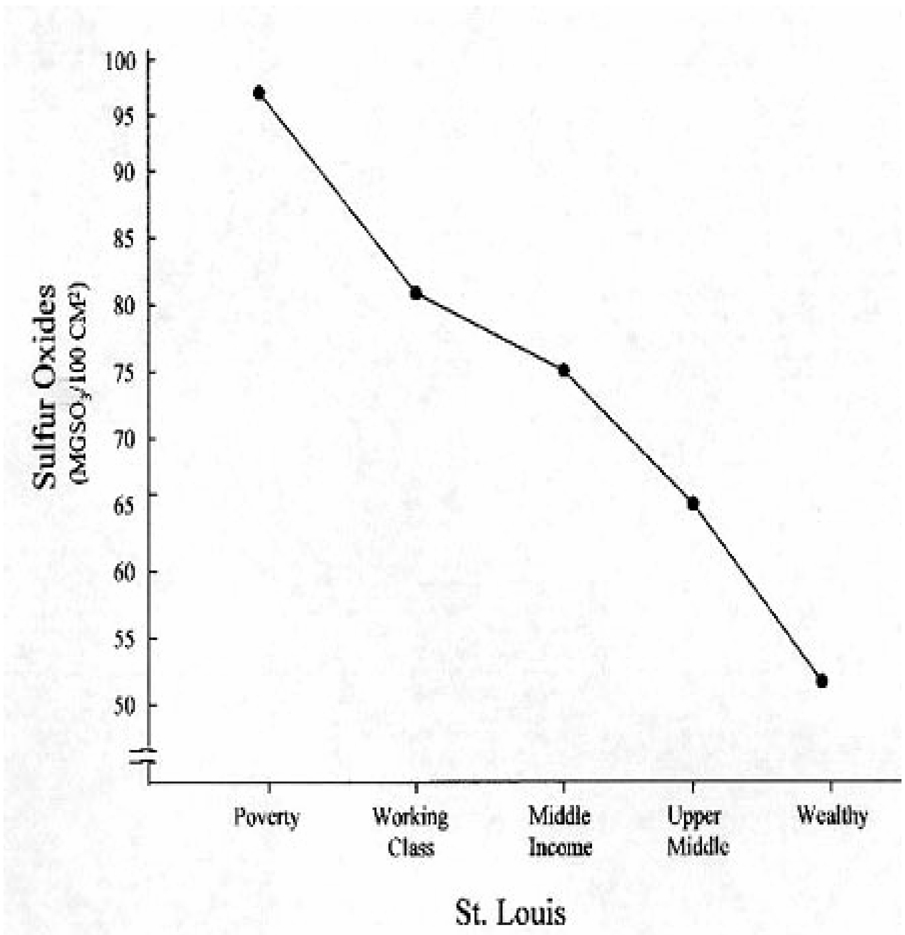

Figure 8. Air Quality and Income Levels in St. Louis (Freeman, 1972)

6.2 Security Measures

Over the past decade, security efforts at water utilities have grown dramatically. The Critical Infrastructure Partnership Advisory Council (CIPAC) developed fourteen features of Findings of the Measures Testing Group (MTG) for National Aggregate Measures of Water Security. (2006).

1. Make an explicit and visible commitment of the senior leadership to security.
2. Promote security awareness throughout the organization.
3. Assess vulnerabilities and periodically review and update vulnerability assessments to reflect changes in potential threats and vulnerabilities.
4. Identify security priorities and, on an annual basis, identify the resources dedicated to security programs and planned security improvements, if any.
5. Identify managers and employees who are responsible for security and establish security expectations for all staff.
6. Establish physical and procedural controls to restrict access to utility infrastructure to only those conducting authorized, official business and to detect unauthorized physical intrusions.
7. Employ protocols for detection of contamination consistent with the recognized limitations in current contaminant detection, monitoring, and surveillance technology.
8. Define security-sensitive information, establish physical and procedural controls to restrict access to security-sensitive information as appropriate, detect unauthorized access, and ensure information and communications systems will function during emergency response and recovery.
9. Incorporate security considerations into decisions about acquisition, repair, major maintenance, and replacement of physical infrastructure; this should include consideration of opportunities to reduce risk through physical hardening and the adoption of inherently lower risk design and technology options.
10. Monitor available threat-level information; escalate security procedures in response to relevant threats.
11. Incorporate security considerations into emergency response and recovery plans, test and review plans regularly, and update plans as necessary to reflect changes in potential threats, physical infrastructure, utility operations, critical interdependencies, and response protocols in partner organizations.
12. Develop and implement strategies for regular, ongoing security-related communications with employees, response organizations, and customers.
13. Forge reliable and collaborative partnerships with communities, managers of critical interdependent infrastructure, and response organizations.
14. Develop utility-specific measures of security activities and achievements, and self assess against these measures to understand and document program progress

Figure 9. CIPAC's Fourteen Features for Water Security

These fourteen features do not define any standard measures for use in a general model. In fact, Feature 14 recommends that utility specific measures be developed. However, Feature 6 is actually in direct conflict with some other social sustainability goals. Feature 6 intends to limit access to utility property to only those people who have official business needs. The creation of green space around utility infrastructure for recreational uses is discouraged by this recommendation, demonstrating the difficulty of developing consistently useful social sustainability measures.

6.3 Targeted Survey of Industry Experts

A survey form (Appendix A) was created to query a small group of experts for their perception of the usefulness of the measure and the availability of data to calculate the measure. The measures included in the questionnaire are as follows:

- **Average Water Bill / Median Household Income –** the basic affordability measure used by EPA

- **Hypothetical Water Bill for Non Discretionary Water Use / Median Household Income –** An alternative affordability measure to account for the minimum water use that a household should be faced with. The American Water Works Association uses 6,000 gallons per month as a standard factor for non-discretionary water use per household.

- **# of Jobs Created At Utility By Water Supply Expansion Project –** local labor market impact of water system expansion

- **# of Jobs Created In Community By Water Supply Expansion Project** - local labor market impact of industry brought to the area or made possible by water system expansion

- **Percent of Minimum Demand Utility Can Supply When Largest Water Treatment Plant is Non-Functional** - A reliability of supply focused indicator at the treatment plant level

- **Expected Duration to Meet Minimum Demand on Backup Power After Power Loss –** A resilience of operations indicator

- **Population within a specified distance of Chlorine Storage –** A physical security indicator related to the potential exposure to toxic chlorine leak

- **Customer – Hours of Service Lost Due To Water Main Breaks** - A reliability of supply focused indicator at the distribution system level

- **Customer – Hours of Service Lost Due To Sewer Collapses** - A reliability of supply focused indicator at the sewer collection level

- **# People Participating in Educational Programs Provided By Utility –** a social outreach measure

- **Percent of Impacted Population Represented in Public Comment Opportunities –** a community involvement indicator

- **Area Created for Parks and Green Space –** a community outreach measure by providing parkland for community

- **# People Using Water Resources for Recreation** - a community outreach measure by providing fishing, boating and other water based recreational opportunities for the area

- **Benefits to Distressed Communities / Costs borne by Distressed Communities –** and environmental justice measure to see if the beneficiaries of the expansion of the water system are proportionally bearing the cost or being provided the benefits

- **# Population with Reduced Exposure to Contaminants –** a public health measure

Each of the indicators was rated on a 1 to 5 scale with 1 being "strongly disagree" and 5 being "strongly agree" to statements regarding usability and data availability. The usability statement was "Managers at water/wastewater utilities would potentially be able to use this measure to assist in making decisions about water supply alternatives." For data availability, the statement was "Managers at water/wastewater utilities would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship." The survey forms were completed by the professionals in the water industry who are serving, or have served, as:

- Former Chair of AWWA's Water Resources Division
- Former General Manager of Virginia's largest water utility
- Director of Planning at a East Coast water utility serving over 1 million people
- Former Director of Engineering at multiple large utilities and current Chair of a national water utility security committee
- Executive Director of an international water resources association
- Program Manager for water security at a large international water association
- Consultant with over 25 years experience on water regulation issues including leading EPA project on Affordability of Safe Drinking Water Act.

Some of the respondents also completed an additional section where they identified the top 5 most important measures for water supply planning (Group A) and the second 5 most important measures (Group B) of the 15 in the sample. The measures rated in the Group A by all responses were considered to be the Most Important for Water Supply Planning. Those measures which were always rated in Group A or Group B were considered of medium importance for water supply planning. Measures that had responses that were predominantly in the lowest third and without any responses in the top third (Group A) were considered to be of lower importance for water supply planning.

It is critical to note that the importance is only related to the planning and analysis of water supply alternatives, not overall importance to the utility. For example, population within a specified distance of Chlorine storage is a critical measure for water utility security management, but appears to be of relatively limited importance when evaluating water supply alternatives.

The responses for each measure are provided in Table 5.

Table 5. Targeted Survey Results

Measure	**Usability**	**Data Availability**
Measures Rated Most Important ***for Water Supply Planning Purposes***		
Expected Duration to Meet Minimum Demand on Backup Power After Power Loss	4.5 (0.5)	4.4 (0.5)
Percent of Minimum Demand Utility Can Supply When Primary Water Treatment Plant is Non-Functional	4.5 (0.5)	4.2 (0.8)
Average Water Bill / Median Household Income	4.3 (0.5)	4.4 (0.5)
Customer – Hours of Service Lost Due To Water Main Breaks	4.3 (0.8)	4.4 (0.9)
Measures Rated Medium Importance ***for Water Supply Planning Purposes***		
Customer – Hours of Service Lost Due To Sewer Collapses	4.0 (0.8)	4.3 (1.0)
Water Bill for Discretionary Usage / Median Household Income	4.0 (0.0)	3.6 (1.1)
Benefits to Distressed Communities / Costs borne by Distressed Communities	3.8 (1.2)	3.2 (1.3)
Measures Rated Medium Importance ***for Water Supply Planning Purposes***		
Area Created for Parks and Green Space	4.2 (0.8)	4.6 (0.5)
Population with Reduced Exposure to Contaminants	4.0 (0.6)	3.4 (1.5)
Population within x miles of Chlorine Storage	3.8 (1.5)	3.8 (1.6)
# People Using Water Resources for Recreation	3.7 (0.8)	3.8 (0.8)
# People Participating in Educational Programs Provided By Utility	3.7 (1.4)	3.6 (1.1)
# of Jobs Created In Community By Project	3.2 (0.8)	3.4 (0.9)
Percent of Impacted Population Represented in Public Comment Opportunities	3.0 (0.9)	3.2 (1.3)
# of Jobs Created At Utility By Project	2.8 (1.2)	3.2 (1.5)
NOTE: Values shown represent the mean. Standard deviation is shown in parentheses.		

6.4 Analysis of Social Measures

In an attempt to categorize the many facets of social measures that could potentially be used in the goal program used to analyze water supply options, the literature was searched for a relevant framework to facilitate analysis. Based on the underlying literature review, it's interesting that the social measures seem to fit the psychological framework of Maslow's hierarchy of needs. Maslow's hierarchy proposes that a person's physiological needs must be met first. Once those lowest level needs are met, the person's decisions are driven by a need for safety. Following safety, as sense of belonging, then esteem (achievement), and self actualization (morality) represent the levels of importance (Huitt, 2004). Extrapolating this hierarchy from a single person to society as a whole, a list of fifteen candidate measures was developed from the literature and categorized by Maslow's hierarchy. The measures analyzed in the targeted survey yield coverage of all levels when placed in Maslow's hierarchy, as shown in Figure 10.

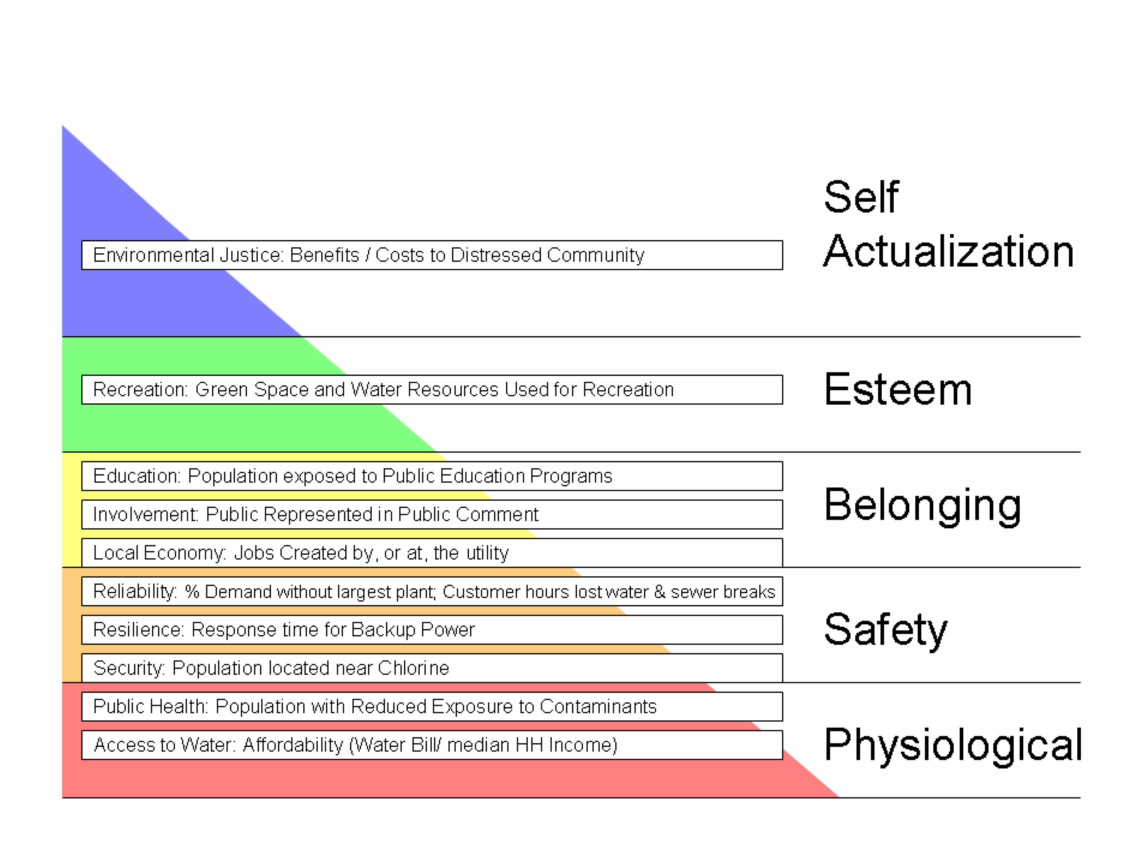

Figure 10: Candidate Social Measures

Based on the targeted survey responses, both numeric and added commentary, the social sustainability indicators showing the most promise for use are related to affordability, reliability, and resilience, which represent the lowest two levels of Maslow's hierarchy. Those measures are:

- Customer – Hours of Service Lost Due To Water Main Breaks
- Percent of Minimum Demand Utility Can Supply When Primary Water Treatment Plant is Non-Functional

- Expected Duration to Meet Minimum Demand on Backup Power After Power Loss

- Customer – Hours of Service Lost Due To Sewer Collapses

- Average Water Bill / Median Household Income

One interesting note is how high the environmental justice indicator (Benefits to Distressed Communities / Costs borne by Distressed Communities) scored. The measure was ranked in the middle third in terms importance and received median usability score, despite potential issues in data availability.

These measures were evaluated based on a small targeted survey of industry experts, both decision makers at utilities and policy influencers at associations. The primary purpose for this survey was to develop a starting point for selection of social sustainability measures to be used in the demonstration of the goal programming framework. Larger surveys or regional surveys may yield different results.

7 DEMAND FORECAST MODIFICATION

Planning for the future requires a target demand forecast at which to aim. Conservation can be treated as a source of water. In integrated water resource planning, conservation can be considered as a resource option in determining the “optimal” resource mix. Conservation can be viewed as a supplemental or even an alternative technology for meeting safe drinking water needs (Beecher, Flowers, and Matzke, 1998). Water conservation is considered to be a demand based approach in which the ways to reduce demand is taken into account instead of finding new solutions to increase the supply. This research is considering both supply and demand side planning, and conservation will be discussed as a demand management technique to modify the demand forecast prior to the goal programming model. This is due to the fact that conservation programs can be implemented much faster and less expensive than capital construction. Because of this fact, conservation impacts will be part of the pre-processing done to refine the demand forecast prior to the model run. Some of the techniques used for water conservation are discussed in the following sections. The conservation alternatives can be analyzed relatively quickly by using existing such as ConservIT (a screen shot is shown below in Figure 11) and modifying the demand forecast prior to running the long term goal program (deMonsabert, Sullivan, and Liner, 2002).

Regional Usage Patterns

Please Select the City (or US national average) closest to your weather and demographic information: **US Average (AWWARF)**

Indoor Usage as % of Total Usage	40.7%		Residential Accounts		3,855
User override					
	Toilet	Washer	Shower	Faucet	Dishwasher
Fixture Usage as % of Indoor Usage	26.7%	21.7%	16.8%	15.7%	1.4%
User override					

Water Conservation Programs Data

	Toilet	Washer	Shower	Faucet	Dishwasher
Consider Fixture in Program Evaluation?	yes	yes	yes	yes	yes
Estimated Penetration Rate	40.0%	40%	40%	40%	40%
% of Fixtures that are already conserving	18.0%	20%	20%	20%	20%
Maximum Replacement %	82.0%	80.0%	80.0%	80.0%	80.0%
Average No. of Fixtures per Account	2	1	2	3	1
Total Fixtures to be replaced (if program chosen)	2,529	1,234	2,467	3,701	1,234

Indoor Conservation Performance

	Toilet	Washer	Shower	Faucet	Dishwasher
Fixture Applance Performance Units	gal per flush	gal per load	gal per min	gal per min	gal per load
Current Fixture Usage (Average)	3.48	41.5	4	2.5	8.5
Conserving Fixture Usage	1.6	25.8	2.5	1.5	8.5
Percent Savings from Fixture retrofit	59%	38%	38%	40%	0%
Pecent Indoor Savings Achieved by Fixture Level	5.16%	2.63%	2.02%	2.01%	0.00%
Percent of Indoor water usage reduction	11.81%				

Conservation Program Costs

	Toilet	Washer	Shower	Faucet	Dishwasher
Unit Installation Cost - equipment	$ 100	$ 750	$ 15	$ 5	$ 250
Unit Installation Cost - labor	$ 75	$ 75	$ 25	$ 25	$ 75
Total Unit Installation Cost	$ 175	$ 825	$ 40	$ 30	$ 325
Total Cost of Fixtures + Labor	$442,554	$1,017,720	$98,688	$111,024	$400,920

Outdoor Conservation Programs

Consider Outdoor Program in Evaluation?	no
Estimated Aggregate Outdoor Usage % Reduction	40%
Cost of Implementing Program	

Consumer Energy Savings Factors

Clotheswasher loads per day per household	1
Unit energy savings (kWh) per clotheswasher load	0.9
Dishwasher loads per day per household	0.3
Unit energy savings (kWh) per dishwasher load	0.6

Combined Impact of Conservation Programs

	Total Usage	Proportional Reduction	Total Conservation
Indoor	40.7%	11.81%	4.81%
Outdoor	59.3%	0.00%	0.00%
% Decrease in Total Residential Demand			**4.8%**

Figure 11. Example of Preprocessing for Demand Forecast Modification Due to Conservation Initiatives

The following sections present a discussion of some of the techniques used in conservation as a means to modify the projected demand.

7.1.1 Demand-side Management

The EPA defines two categories of water use efficiency practices. The first category includes the 'Engineering practices' that are based on modification in plumbing, fixtures, or water supply operating procedures that use less water. Residential demands account for about three-fourths of the total urban water demand. Indoor use accounts for roughly 60 percent of all residential use. In existing residences replacement of conventional appliances with modern water conserving equipment is a practical and economical alternative. Recent technological developments can help reduce water waste since there are many innovative techniques and strategies that encourage wise use of water. The second category belongs to the 'Behavioral practices' that are based on changing water use habits. The effectiveness of individual conservation techniques is limited when implemented separately, and strengthened when part of a well-designed program (Mee, 1996). In establishing an effective water conservation program, all potential water saving measures should be considered and evaluated under given criteria. The following attributes may be included in the demand-side alternative framework:

- Capital Costs
- Operating and Maintenance (O&M) Costs
- Reduction in consumption (and associated revenues)
- Expected duration of demand modification
- Impact on environmental and social goals (capital and O&M costs will address the economic goal achievement)

7.1.2 Public Education

For the success of such programs, community involvement and support is necessary. The customers' education about the value of water is essential to ensure effective community response towards these programs. The conservation programs dealing with the behavioral changes are less reliable resource options because they are dependent on unpredictable end users' behavior. Also the behavioral change is not much persistent with time. These programs are always very responsive by the people in the beginning. But as the time passes by, the effectiveness of such programs along with the community interest fades away. A periodical effort regarding education and awareness about the benefits of a program plays an essential role in a long-term success of that program.

7.1.3 Water Efficient Fixtures

There are many innovative techniques and practices to obtain water efficiency in domestic water use. According to a study by the American Water Works Association Research Foundation (AWWARF), a typical single family home, with no water conservation fixtures, uses 72.5 gallons of water per person a day. By installing readily available water efficient fixtures/appliances and taking measures to minimize leaks, the use of water can be reduced to 49.6 gallons per person a day which accounts to a 32% reduction. (Residential End Uses of Water, 1999)

7.1.4 Xeriscape

The landscape is the most demanding part of the domestic water use. In Urban areas between 40 to 60 percent of water supply is used for landscape and garden watering. In a traditional landscaping only one or two principles of water conservation can be established. Xeriscape can be defined as 'a quality landscaping that conserves water and protects the environment utilizing the entire notion of landscape water conservation'. The Front Range Xeriscape Task Force of the Denver Water Department coined the term Xeriscape in 1981 for water conserving landscaping. It is derived from the Greek word xeros meaning dry, combined with landscaping to make Xeriscape that means 'water conservation through creative landscaping'. Xeriscape is not only "rock and cactus" garden as it has been understood in the past. Xeriscape can be beautiful, functional, beneficial to the environment, and require less maintenance than traditional landscapes (Kavouras, 1996). A quality Xeriscape if properly maintained uses about one-third of the water of a traditional landscape, requires less maintenance, fertilizer and pesticide.

7.1.5 Conservation Policies

Imposing and mandating water conservation policies by the government are very effective for efficient water use especially when the incentives for water conservation are not provided. The federal and state governments have accepted conservation measures as part of their water resource planning management practices. The Energy Policy Act 1992, established plumbing fixture water efficiency standards that are expected to have a marked effect on US water use over the next 25-30 years, particularly among residential customers. The Act requires that all new homes and major remolding nationwide incorporate water-efficient fixtures and appliances. The analysis of historic trends indicates that water use is reduced as a result of water conservation programs in several regions of the United States. According to a study by the United States Geological Survey, water use dropped by 9% even since the population grew by 16%, between1980 and 1995 (Turning off the Tap, 1998). Not only the per capita water use is declining, but also the total use is decreasing. This trend in total use suggests that conservation and regulations are having an impact on water use.

The Safe Drinking Water Act (SDWA) amendments of 1996 include a brief provision concerning water conservation planning. The amended SDWA requires USEPA to publish conservation guidelines but states are not required to adopt the guidelines or to use them in conjunction with their Drinking Water State Revolving Fund (DWSRF) programs. Congress identified water conservation as a potential screening criterion for use in the DWSRF (Beecher et. al, 1998). Also several states have their legislation dealing with water conservation and mandate residential retrofit program for utilities depending on the size and certain characteristics of a utility.

8 GOAL PROGRAMMING MODEL GENERAL FORM

In order to utilize goal programming to help provide insight into decision making for an integrated water supply plan, the process shown in Figure 12 can be used.

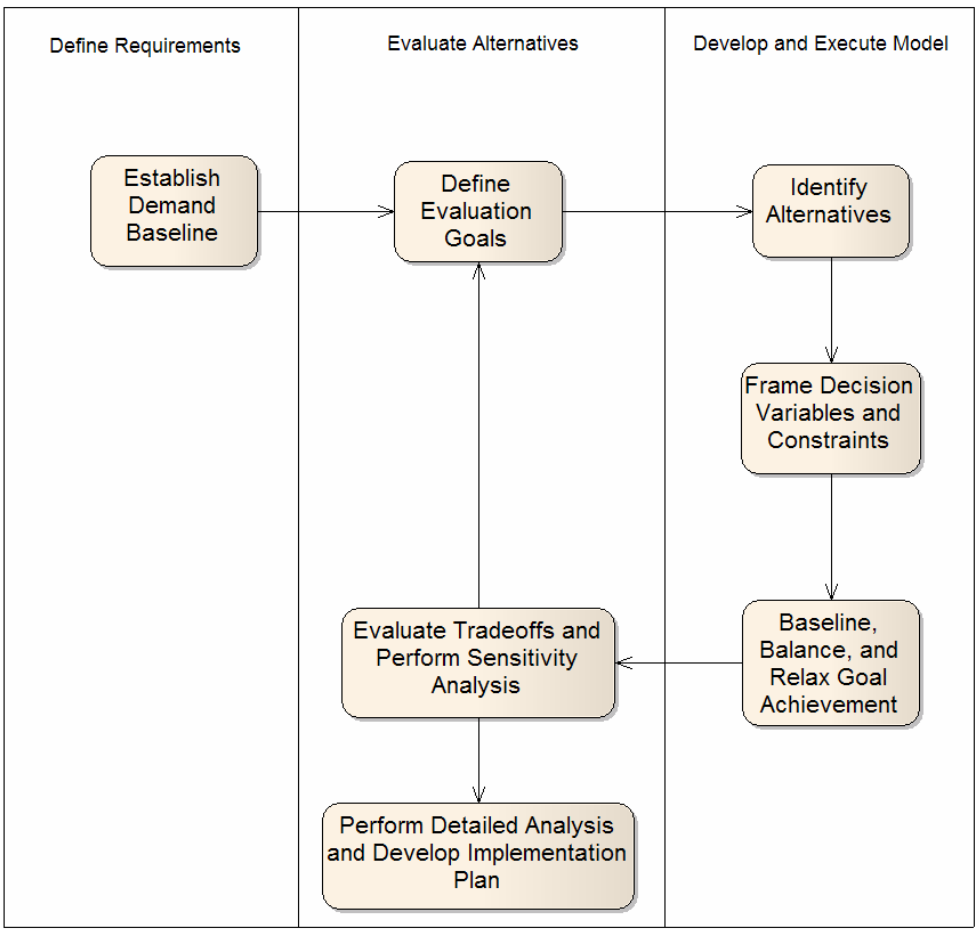

Figure 12. Goal Programming Process

Each of the steps shown above is discussed in the following sections.

8.1 Establish Demand Baseline

The first step is to determine the requirements of the plan – what demand does the plan have to meet? Before entering the modeling stage, modify the demand forecast with any conservation programs that may be used in order to create a baseline. In parallel, the utility financials and water supply capacity should also be baselined to establish a status quo.

8.2 Define Evaluation Goals

In following with the axiom "begin with the end in mind," the performance measures that can possibly be used to construct the three sustainability goals should be identified. In order to develop the goals that will be used in the model, the following data are needed:

- Performance Measure(s) Definitions – to ensure consistent calculation across all measures.

- Magnitude and Direction of Goodness – a best and worst case (or allowable values) are needed to normalize the components and calculate the progress towards a target or threshold.

- Relative Weighting of Measure Within Goal – some components of the goal may be relatively more important than others. For the initial runs in the model, all factors are weighted equally.

Based on the research presented in Chapters 4 through 6, a good starting point would be to choose from the following Goals for Evaluation Menu. This menu is not meant to be the definitive set of measures, but as a basis for beginning the analysis. Many other measures, discussed in Chapters 4 through 6 and as determined by local conditions, may be incorporated into the model as needed, depending on the specific issues facing the utility.

- **Economic Goal Measures**
    - Annualized Cost of Water Supply Alternative
    - Net Income
    - Operating Ratio
    - Average Water Rate
- **Environmental Goal Measures**
    - Percentage of Water from Renewable Sources
    - Wastewater Reuse Percentage
    - Total Waste Discharged – nutrients (P, N, BOD, SS)
    - Volume of Wastewater Discharged to Receiving Body

- Total Energy Usage and Percentage of Energy from Renewable Sources

- **Social Goal Measures**

  - Average Water Bill / Median Household Income
  - Customer – Hours of Service Lost Due To Water Main Breaks
  - Percent of Minimum Demand Utility Can Supply When Primary Water Treatment Plant is Non-Functional
  - Expected Duration to Meet Minimum Demand on Backup Power After Power Loss
  - Customer – Hours of Service Lost Due To Sewer Collapses

8.3 Identify Alternatives

Each of the potential alternatives should be defined in terms of capacity, cost, and contribution to the performance measures. In some cases, the alternatives will have unit contribution toward goal achievement; while in others, the measure will be calculated after the aggregation of the impacts of the combination of selected alternatives.

8.4 Frame Decision Variables and Constraints

8.4.1 Decision Variables

The decision variables are set up to determine when an alternative is needed to come on line. Since the implementation activities (design, construction, testing) may take years to complete before a source can be put into production, it is important to account for the difference from the time to start a project and the time the source will be producing. Over a long planning horizon of 25 to 50 years, there is ample time to begin construction before the source is required. Care must be taken to ensure consistency between project start and production. For example, if bond proceeds are used for funding an alternative and debt service payments must be made during construction, these costs need to be accounted for in the model and the production should be lagged for the duration of the construction of an alternative (i.e., costs could begin in year i, while production may begin in year $i+3$, assuming a three year design and construction cycle). These construction timeframes may vary by alternative, as building a dam is generally a longer term project than drilling wells, for example.

Timing can be important in terms all three goals. Deferred capital costs are the primary reasons for delaying a project until the capacity is needed. Deferring capital expenses mean that if an expansion that was going to have to take place in year 1 was pushed back until year 3 due to reduced demand from conservation programs, the extra two years of not having to pay debt service on the capital expansion are a financial benefit. On the other had, implementing a solution earlier may provide better achievement to an environmental goal measure (reuse water, for example) or social goal measure (such as reliability). Therefore the decision variables are binary variables x_{ij} where i is the year and j is the alternative. If the model recommends that alternative j is brought into service in year i, then $x_{ij} = 1$, else $x_{ij} = 0$.

8.4.2 Constraints

The primary constraints (not related to the TBL goals) are related to capacity (supply must exceed demand, but not have wasted excess capacity) and uniqueness (An alternative can only be built once). The constraints for these conditions are as follows:

Uniqueness

$$\sum_{i=1}^{n} x_{ij} \leq 1 \text{ for each } \boldsymbol{j} = 1..\boldsymbol{m} \text{ alternatives} \tag{13}$$

Capacity Constraints

$$CAP_{Utility}^{i} = CAP_{Utility}^{i-1} - CAP_{Degradation}^{i} + \sum_{j=1}^{m} x_{ij} CAP_{j} \text{ (Total Capacity including new alternatives and degradation of existing supply)} \tag{14}$$

Where $CAP_{Utility}^{i}$ is the total water supply capacity of the utility at time ***i***, $\boldsymbol{CAP_j}$ is the incremental capacity of alternative ***j***, and $CAP_{Degradation}^{i}$ is any degradation of existing sources of supply, such as permitted flow reduction, plant retirement, or expiration of purchase agreements.

$$CAP_{Utility}^{i} \geq D_{i} \text{ (Capacity Sufficient to Meet Demand)} \tag{15}$$

$$CAP_{Utility}^{i} \leq CAP_{Max} \text{ (Limitation of “overbuilding”)} \tag{16}$$

Where $\boldsymbol{D_i}$ is the demand in period $\boldsymbol{i}$ and $\boldsymbol{CAP_{Max}}$ is the maximum value of capacity to ensure the utility doesn't build excess capacity that it won't utilize during the planning horizon. The determination of $\boldsymbol{CAP_{Max}}$ is specific to each utility. There are a number of options to define the number (or set of numbers). The factor could be determined as a single number (for example, the demand at the end of the planning horizon), a percentage of capacity in each year (say, 150 percent of peak demand), or the demand a fixed time into the future (i.e., meet the demand for the year 10 years from current year).

8.5 Baseline, Balance, and Relax Goal Achievement

After defining the goals, the maximum goal achievement threshold $\mathbf{G_k}$ for $\mathbf{k} \in$ {Economic, Environmental, and Social} must be established in order to normalize the goals. This ***Baseline*** can be accomplished by maximizing each goal individually without any contribution from the other goals. Once the normalizing factors are determined, a maximin problem is solved to ***Balance*** the goal achievement by maximize the minimum goal achievement for all three goals. As discussed in Section 3.4.1.2, the general form of this optimization problem is:

Maximize $\quad Z = \boldsymbol{z}$ (4)

Subject to:

$$z \le \frac{\sum_{j=1}^{n} c_{jEconomics} x_j}{G_{Economics}} \quad \text{Economic goal achievement} \qquad (5)$$

$$z \le \frac{\sum_{j=1}^{n} c_{jEnvironmental} x_j}{G_{Environmental}} \quad \text{Environmental goal achievement} \qquad (6)$$

$$z \le \frac{\sum_{j=1}^{n} c_{jSocial} x_j}{G_{Social}} \quad \text{Social goal achievement} \qquad (7)$$

Plus the capacity constraints discussed in Section 8.4.

The value of the objective function in the balanced run is the maximum minimum goal achievement for all three goals, or $\boldsymbol{Z_{Balance}}$. After obtaining the maximum goal achievement threshold $\boldsymbol{Z_{Balance}}$, the model can be rerun with the model objective to minimize cost (Maximize Economic Goal Achievement) subject to a ***Relaxed*** minimum goal achievement for the environmental and social goals set at intervals below $\boldsymbol{Z_{Balance}}$

$$\text{Maximize Z=}\frac{\sum_{j=1}^{n} c_{jEconomics} x_j}{G_{Economics}} \qquad (17)$$

Subject to:

$$z' \le \frac{\sum_{j=1}^{n} c_{jEnvironmental} x_j}{G_{Environmental}} \quad \text{Environmental goal achievement} \qquad (18)$$

$$z' \le \frac{\sum_{j=1}^{n} c_{jSocial} x_j}{G_{Social}} \quad \text{Social goal achievement} \qquad (19)$$

Where $\boldsymbol{z'}$ is the relaxed minimum goal achievement level.

8.6 Evaluate Tradeoffs and Perform Sensitivity Analysis

After obtaining the maximum balanced goal achievement and the results of the relaxed constraint model runs, additional analysis can be performed. A tradeoff curve should be developed comparing the minimum goal achievement for all three goals plotted against the costs of the recommended solutions. From this tradeoff curve, the cost of including environmental and social factors into the analysis can be identified. In addition, the tradeoff can provide information to aid a decision maker in identifying the most politically and technically feasible set of alternatives; that is, how much environmental and social goal progress can the decision maker achieve at an acceptable cost.

Additional sensitivity analysis should also be performed to evaluate the recommended set of alternatives. For example, weighting the component measures within each goal may change the recommended set of alternatives. Various solutions obtained under different weighting schemas may provide additional insight into the selection of a final chosen set of alternatives and schedule for implementation.

8.7 Perform Detailed Analysis and Develop Implementation Plan

The Goal Programming model is intended to provide high level insight into the problem of integrated water supply planning. The recommended solution set of alternatives should be evaluated in detail for final feasibility prior to committing to a master plan.

9 MODEL DEMONSTRATION SCENARIO

9.1 Demonstration Purpose

In order to demonstrate the feasibility of the use of the goal programming framework for municipal integrated water resources planning, real data and plans from a municipal water utility were entered into the model framework. Key issues to be addressed in the demonstration include:

- **Format –** Does the data in the case study correspond to the model variables?
- **Data availability –** Does the model require information that is generally available to a municipal utility?
- **Sensitivity analysis –** Does the model lead to the same solution set regardless of the data inputs and weighting?
- **Identification of additional research needs –** What additional information is needed to enhance the model framework? What questions arise from the results of the model runs?

9.2 Overview of Demonstration Data

A number of publicly available municipal water supply master plans were reviewed to obtain an example of data that encompasses the cost, capacity, and factors related to social and environmental factors as well. Master plans from many utilities across the country including Beaufort-Jasper (SC) Water & Sewer Authority, Bend (OR), Longmont (CO) and Palm Bay (FL) had performance measures, costs, evaluation criteria, and alternatives outlined in their publicly available reports. However, due to a number of factors, The Assessment of Long Term Water Supply Alternatives from Cambria Community Services District (CCSD) in Cambria, California was chosen as the basis for the demonstration (2004). The publicly available report provided all the necessary data to run the goal programming model, including:

- Long range demand forecast, with forecasted population growth and an increase in water usage to enhance quality of life issues.

- Multiple Alternatives with different variable types. For example, a desalination plant could be built with capacity between 300 and 820 Acre Ft/Year (linear decision variable for the size of the plant). Another alternative was a dam and reservoir which had a fixed capacity (either 700 AFY or 0 in the model).

- Extensive discussion of the environmental and social factors for decision analysis including solar electricity, wastewater reuse, wildlife habitat, reliability, and the rating scales used in the decision making at the utility.

- Detailed Cost analysis of the alternatives, with capital costs, fixed O&M costs, and variable O&M costs clearly defined.

The CCSD report utilized multi-criteria utility analysis with eight factors each weighted equally. After the analysis, the recommended solution consisted of a combination of Water Demand Management, Recycled Water, and Seawater Desalination to be implemented as soon as possible. The factors analyzed were:

- Water Supply Capacity
- Water Quality
- Reliability
- Institutional Issues
- Environmental Issues
- Ease of Permitting
- Cost
- External Funding Availability

In order to better demonstrate the capabilities of the GP model, a number of these factors were modified for academic purposes. These modifications have the added benefit of deflecting any potential criticism to the decisions reached by CCSD under their thorough analysis, as the results of the GP model will be an academic proof of concept rather than an alternative recommendation specific to CCSD.

The GP model will provide a set of recommended alternatives under various assumptions. The model will recommend in which year to implement which alternative to maximize the goal achievement in each scenario. Each model run will provide the "best" combination of alternatives over a 24 year planning horizon. The 24 year time horizon was chosen due to the constraints of the academic edition of optimization package. With eight alternatives that could be built in one of 24 years, 192 binary variables exist. The limitation of the solver is 200 integer variables. In addition, twenty four years is a sufficiently long planning horizon for an integrated water supply plan.

The framework of the demonstration data, including elaboration of the modifications, is discussed in the following sections. All specific references will be generalized (CCSD will be referred to as "the utility, and place names will be modified to sound generic).

9.3 Demand Forecast

The utility's current demand is seasonal, with 6,400 year round residents and 20,000 visitors annually. Baseline demand is 810 AFY, as consumed by the 3,812 estimated housing units. Over the next three decades, the utility service area population is expected to grow to between 4,650 and 6,700 residential units. In addition, the unit consumption is expected to increase between 10 and 50 percent to improve "quality of life." For modeling purposes, a 50 percent increase in the unit consumption rate was considered and the maximum build out used to estimate demands. Using these assumptions, the adjusted demand would be 1,215 AFY at year 1 of the analysis and

2,072 AFY at year 24. Year 1 is defined as the first year that an alterative could come on line. With the alternatives under consideration generally estimated to require two to three years for design and construction, Year 1 as defined in the model is effectively three years after the decision to begin implementing alternatives.

Generally, the demand forecast would be adjusted due to conservation alternatives prior to the analysis of supply side alternatives. However, since the utility has already implemented extensive conservation practices, the potential for further reduction is low (Assessment of Long-Term Water Supply Alternatives, 2004). When coupled with the desired increase in unit consumption, the impact of demand management would probably be lost in the noise, and is therefore, not considered in the model.

9.4 Water Supply Alternatives

The utility's baseline permitted water supply capacity stands at 1,230 acre-ft per year (AFY). However due to drought and MtBE contamination in one of the utility's water sources, the realistic capacity to meet high reliability is substantially less. For the purposes of the model, this baseline capacity is set at 800 AFY. Eight alternatives are available for consideration in the supply alternatives:

- Seawater Desalination
- Seawater Desalination with Solar Electricity
- Aquifer Recharge Using Lake Water with Pipeline Route 1

- Aquifer Recharge Using Lake Water with Pipeline Route 2
- Negotiated Exchange of Water Rights and Pipeline
- New Wells
- Recycled Water
- New Dam and Reservoir System

Each of the alternatives is discussed below. The two desalination and two lake alternatives are discussed together.

9.4.1 Seawater Desalination (with and without Solar Electricity)

Seawater desalination from the ocean is very reliable, as the source is neither affected by drought or seasonality. This option considers the construction of an intake pipeline and reverse osmosis (RO) plant. Three discrete plant capacities were evaluated by the utility: 300 AFY, 520 AFY, and 820 AFY. For modeling purposes, the size of the plant was assumed to be continuous. That is, any size RO plant could be constructed between the minimum 300 AFY capacity and the maximum 820 AFY capacity, thus, expanding the alternatives for evaluation.

Since desalination is an exceptionally energy intensive treatment technology, the utility considered the installation of a solar array to generate the electricity required by the RO plant. Grant funding was potentially also available to the utility to offset the costs of solar construction. For modeling purposes, the grant funding was excluded in order to focus on the worst case scenario. Correspondingly, revenues from the sale of excess electricity back to the grid were also excluded. Due to some of the regulatory and funding constraints, construction of a solar power plant would be limited to twice the maximum demand. According to the utility's analysis, a 300 AFY plant would demand 240 kW. Therefore, the maximum solar capacity at 300 AFY would be 480 kW. For modeling purposes, the ratio of water treatment capacity to electricity generation capacity is assumed to be constant (1.6 kW per AFY). The implication is that at the largest desalination plant capacity appropriate for the utility (820 AFY), the solar electricity generation plant would have a capacity of 1,312 kW.

The annual fixed costs (annualized capital cost plus fixed operations & maintenance costs) for the desalination plants are shown in Table 6. Figures 13 and 14 show the linear regression models used to generate a continuous cost curve for use in the GP model. The third cost factor calculated by the utility was variable O&M. For simplicity, the value at the midpoint (560 AFY) of the design capacities was used to generate the expected annual cost for the variable O&M. The estimated variable O&M for a desalination plant without solar is $414,000. Due to the electricity savings from solar power generation, the estimated variable O&M for a desalination plant with solar power generation is $106,000.

Table 6. Desalination Costs
(Assessment of Long-Term Water Supply Alternatives, 2004)

Costs (in $000)	300 AFY	520 AFY	820 AFY
DESALINATION			
Annualized Capital Cost (4% over 30 years)	477	574	739
Fixed O&M Cost	107	132	157
Total Fixed Annual Costs	**584**	**706**	**896**
DESALINATION WITH SOLAR			
Annualized Capital Cost (4% over 30 years)	743	1,083	1,491
Fixed O&M Cost	130	176	216
Total Fixed Annual Costs	**872**	**1,258**	**1,707**

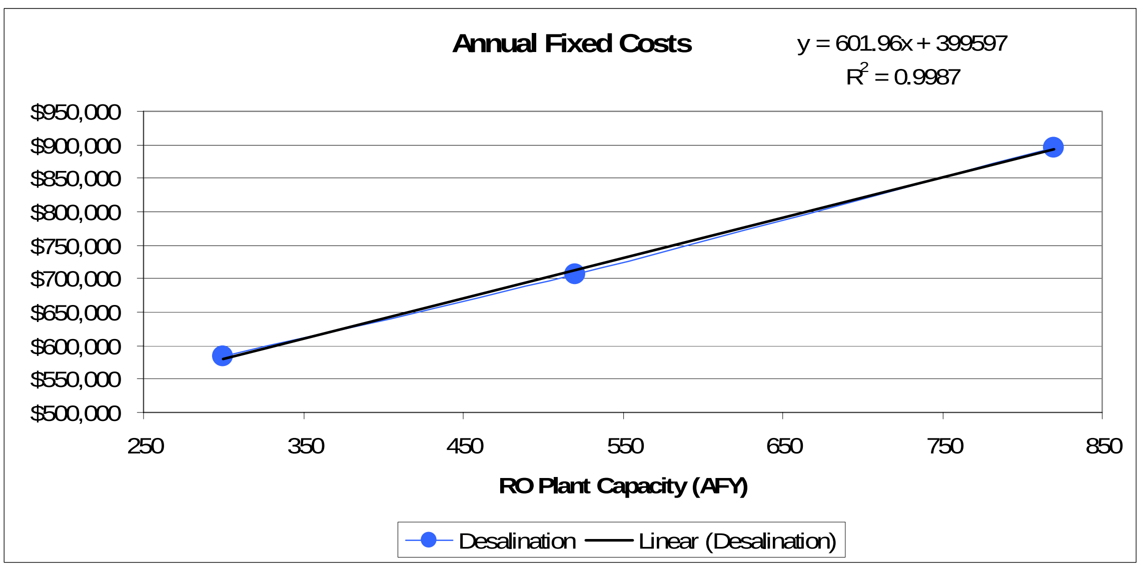

Figure 13. Linear Cost Function for Desalination Plant

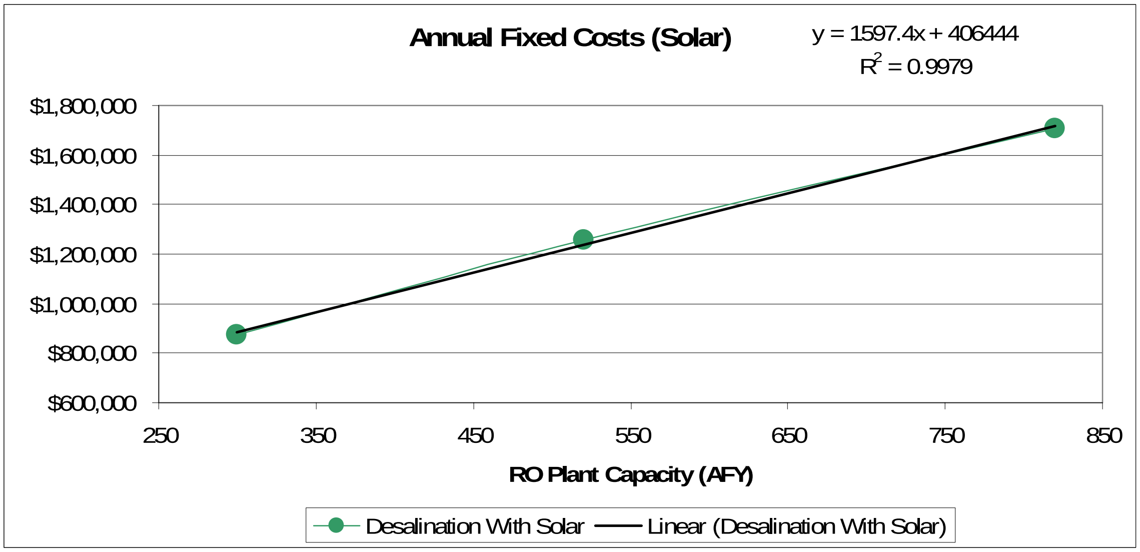

Figure 14. Linear Cost Function for Desalination Plant with Solar Power Plant

9.4.2 Aquifer Recharge Using Lake Water

The utility has a currently unused allocation of 2,000 AFY from a nearby lake. Due to changes in the riparian environment, the actual available capacity is only 730 AFY. The Lake option would withdraw surface water from the lake and pump it to an aquifer recharge basin, where the utility would then use its wells to withdraw water from the aquifer. Two routes are available to pipe the water to the basin. Route 1 is 8.7 miles long and Route 2 is 10 miles total. Both routes have environmental concerns with reptile and amphibians that may be impacted by construction. However, the creek portion of Route 2 provides more habitat for federally threatened Steelhead Trout rearing. Cost estimates are shown in Table 7.

Table 7. Costs Estimates for Pipeline Route Alternatives for Lake Water Aquifer Recharge (Assessment of Long-Term Water Supply Alternatives, 2004)

	Route 1	Route 2
Annualized Capital Cost (4% over 30 years) ($/yr)	$1,023,000	$1,081,000
Fixed O&M Cost ($/yr)	$161,000	$161,000
Variable O&M Costs ($/AF)	$580	$560

9.4.3 Negotiated Exchange of Water Rights and Pipeline

The third type of alternative is the exchange of water rights from the lake mentioned in the previously discussed aquifer recharge option with capacity in a nearby reservoir. In the utility analysis, two variations exist for this alternative: 700 AFY capacity and a 1,000 AFY capacity. The smaller capacity option does requires only incremental modifications to existing infrastructure (pumping stations and treatment plant). The larger option would require a 15 mile pipeline, a 3.8 MGD (million gallon per day) surface water treatment plant, and a 2.2 MG storage tank, increasing capital costs by over $16,000,000, a six-fold increase in capital costs. For modeling purposes, the larger option is excluded and only the 700 AFY variation is considered. Because the water source is an existing reservoir, the environmental and social impacts are mostly due to the pipeline. The cost estimates for the rights exchange alternative are shown in Table 8.

Table 8. Costs Estimates for Negotiated Exchange of Water Rights (Assessment of Long-Term Water Supply Alternatives, 2004)

Cost Component	Cost
Annualized Capital Cost (4% over 30 years) ($/yr)	$222,000
Fixed O&M Cost ($/yr)	$65,000
Variable O&M Costs ($/AF)	$1,920

9.4.4 New Wells

The potential for up to 324 AFY exists through hard rock drilling for a new well. Hard rock water supplies are high-risk ventures, but the drilling company generally assumes the capital risk in order to obtain a long term (typically 20 year) contract to supply water to the utility. The costs for the study of the potential yields would be $250,000 with half coming from the utility. Estimated commodity costs for the ongoing supply are $1,000 per AF of water delivered (Assessment of Long-Term Water Supply Alternatives, 2004).

9.4.5 Recycled Water

This alternative involves the use of recycled wastewater for outdoor, non-potable uses to reduce the potable water demand. This irrigation demand is estimated to be 160 AFY at the expected potential users. These users are expected to be non-residential sites such as community parks, camp grounds, schools, churches, and cemeteries. The environmental effects would be related to the pipeline and potential long-term impacts on groundwater quality due to the seepage from the irrigation. However, no major environmental concerns should be encountered, since this option does not required any changes to watersheds or land use. Simply the use of recycled water (sometimes called reclaimed water or reuse) is a favored environmental sustainability metric, as shown in Chapter 5.

The costs for recycled water are generated by pipeline construction, storage, and incremental modifications to the existing wastewater treatment plant to ensure that the effluent quality meets regulation for non-potable usage. The cost estimates for the recycled water are shown in Table 9.

Table 9. Costs Estimates for Recycled Water
(Assessment of Long-Term Water Supply Alternatives, 2004)

Cost Component	Cost
Annualized Capital Cost (4% over 30 years) ($/yr)	$336,000
Fixed O&M Cost ($/yr)	$33,000
Variable O&M Costs ($/AF)	$810

9.4.6 New Dam and Reservoir System

The final alternative is the construction of a new dam and reservoir system. The utility analysis has two variations on this alternative. In order to streamline the model, only one of these variations was analyzed. Both variations had similar general impacts in terms of environmental concerns and institutional issues. However, one alternative had lower fixed costs, lower variable costs, and would flood a smaller acreage to achieve the same 700 AFY capacity. Since this alternative would be the dominant choice between the two reservoir options, the lower cost option was analyzed. In addition, the higher cost option had the potential for Native American archeological sites, making a greater negative impact on the social sustainability scale.

The cost estimates for the recycled water are shown in Table 10.

Table 10. Costs Estimates for New Dam and Reservoir System (Assessment of Long-Term Water Supply Alternatives, 2004)

Cost Component	Cost
Annualized Capital Cost (4% over 30 years) ($/yr)	$500,000
Fixed O&M Cost ($/yr)	$59,000
Variable O&M Costs ($/AF)	$100

9.5 Utility's Evaluation Criteria

The utility evaluation of the alternatives ranked each alternative on eight criteria valued on a categorical scale from 1 to 5. These criteria and scores served as the basis for the goal development in the model. The definitions of the category rankings are shown in Figure 15.

SUMMARY OF THE CRITERION RANKING SCALE

Criteria	1	2	3	4	5
Water Supply Capability (AFY)	< 600	600 – 750	750 - 850	850 – 1,000	> 1,000
Water Quality	Very Poor	Poor	Fair	Good	Excellent
Reliability	None	Little	Less than Sufficient	Sufficient	More than Sufficient
Required Agreements/ Institutional Issues	Very Difficult to Obtain	Difficult to Obtain	Obtainable	Relatively Easy to Obtain	None Required
Environmental Issues	Significant Impacts, Further Review Required	Significant, but Short-Term	Less than Significant, After Mitigation	No Significant Impacts	No Impacts
Permitting/CEQA	Very Difficult to Obtain	Difficult to Obtain	Obtainable	Relatively Easy to Obtain	None Required
Cost (Fixed/Variable)	Above/Above Average	Above/Below Average	Average/Average	Below/Above Average	Below/Below Average
Funding (reduction in capital cost)	None	25 percent	50 percent	75 percent	100 percent

Figure 15. Utility Baseline Evaluation Criteria
(Assessment of Long-Term Water Supply Alternatives, 2004)

Three of the eight criteria used as performance measures related to economic goals were not used as directly specified by the categories described in Figure 15. "Water Supply Capability" was excluded as part of a goal, as the capacity of each alternative was directly enumerated and used to meet the primary constraint of capacity meeting demand. As discussed above in Section 9.4.1, the "Funding (reduction in capital cost)" criterion was removed in order to focus on the worst-case scenario. The "Cost (Fixed/Variable)" criterion was not taken into account as a categorical variable, as the costs were directly enumerated for the economic goal.

Five of the eight criteria were directly used as performance measures to construct the environmental and social goals. “Reliability” was used as a performance measure in the social goal framework. “Required Agreements/Institutional Issues” and the “Permitting” criteria were also included in social goal development as proxies for public involvement in the planning process, social aspects such as Native American archaeological sites, and recreational issues such fishing habitat.

The “Water Quality” and “Environmental Issues” were directly used as components of the environmental goal. Table 11 shows how each of the water supply alternatives scored on the categorical scale in the utility study. One modification was made to the utility study scoring in order to provide additional variation to test the model’s analytical framework. The “Environmental Issue” score for Route 2 of the Aquifer Recharge Using Lake Water option was increased from a “2” in the utility report to a “3” in the academic analysis. This adjustment was partially justified because the Route 2 option provides additional environmental benefits from improved Steelhead Trout habitat.

Table 11. Criteria Scoring for Water Supply Alternatives

Water Supply Alterative	Water Quality	Environmental Issues	Permitting	Reliability	Institutional Issues
Desalination	1	3	2	5	2
Desalination with Solar	1	3	2	5	2
Lake Recharge, Route 1	4	2	3	2	2
Lake Recharge, Route 2	4	3	3	2	2
Exchange of Water Rights	3	3	4	2	1
New Wells	3	1	3	3	3
Recycled Water	1	3	3	5	4
Dam & Reservoir System	2	2	3	1	2

9.6 Goal Development

The following sections will discuss the goal development for the demonstration scenario.

9.6.1 Economic Goal Development

After looking at the balance sheet and income statement for the utility, the most straightforward economic goal consisted of a single measure: present value of the aggregate annual costs for the new water supply projects. This includes the amortized capital costs, fixed O&M costs and variable O&M costs. A value of 0 might arbitrarily be assigned to the "best" condition. However, in order to determine a more realistic "best" goal achievement for the economic goal, a model run simply minimizing costs subject to capacity constraints was run, eliminating any contribution from the environmental and social goal. The challenge is to develop the "worst" case.

Mathematically, the worst case would be the total cost for building all of the options at year 1. However, this approach would be as arbitrary and unrealistic as assuming a zero cost as the "best" case. When looking at the potential measures in total across all aspects of the TBL, it became obvious that rate increase and affordability issues would be directly correlated to the overall cost. Therefore, the economic goal was developed with the social measure of affordability in mind. The "worst" case value was developed by taking the median household income and multiplying by the two percent affordability threshold for the entire service area. Thus the "best" case is when costs are minimized without regard to environmental and social concerns. The "worst" case is defined as the level at which water rates cross the threshold from affordable to unaffordable.

9.6.2 Environmental Goal Development

Two environmental measures (Environmental Issues and Water Quality) were taken directly criteria in the utility analysis. Each was rated on the 1 to 5 scale as shown in Table 11. Based on those numbers, the best and worst cases for Environmental Issues were 3 and 1, respectively. For Water Quality, the values were 4 and 1 for best and worst cases.

Two additional measures were added as part of the model demonstration to correspond to the menu of environmental performance measures: Renewable Energy Production and Use of Reclaimed Wastewater. Each of these measures only applied to one alternative. The Renewable Energy Production would be defined as the size, in kW, of the solar array used at the desalination plant. The best case would be the maximum size of solar facility that could be constructed (1,312 kW). The worst case would be 0, which would be the contribution earned for all options except for the desalination with solar. Similarly, the Use of Reclaimed Wastewater would only be applicable to the Recycle Water alternative. The best case would be maximum utilization (or 160 AFY) and the worst case would be zero.

9.6.3 Social Goal Development

With possibly the most important social measure already addressed by using affordability in conjunction with the cost goal to set the boundaries of the best and worst cases, the social performance measures were taken directly from the utility analysis. Permitting, Reliability, and Institutional Issues are the three performance measures that were used in constructing the social goal. Permitting values for the water supply alternatives ranged from a low of 2 to a high of 4. Reliability values spanned the entire 1 to 5 range. Institutional Issues ranged from 1 to 4.

10 MODEL RESULTS

Running the goal programming model entailed entering all of the data in Chapter 9 into a spreadsheet and applying the general principles described in Chapter 8 to solve the goal program. Multiple model runs were made using the Lindo Systems add-in: ***What'sBest!®*** 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363.

10.1 Model Setup

10.1.1 Supply, Demand, and Costs

As discussed in Chapter 9, the demand in year 1 of the study, D_1, was set to 1,215 AFY. For the demand in year 24, D_{24}, the demand was 2,072 AFY. The increase over time followed the demand forecast in the utility analysis. Baseline capacity, CAP_0, was set at 800 AFY. Incremental capacities for each of the alternatives, CAP_{ij}, are shown in Table 12.

Table 12. Water Supply Capacity of Alternatives

Alternative	Incremental Capacity (AFY)
Desalination	Variable between 300 and 820
Aquifer Recharge By Lake Water	730
Negotiated Exchange of Water Rights	700
New Wells	324
Recycled Water	160
Dam and Reservoir System	700

With the supply and demand factors in place, the next steps were to define the measures comprising the goals. The annualized costs from each alternative were applied across the entire planning horizon to obtain the temporal effects of implementing each alternative. That is, if an alterative is brought into service in year 1, then the costs will be incurred all 24 years of the planning horizon. If in year 2, then only 23 years of costs will be incurred, and so on. These values were pre-calculated and placed into a coefficient matrix to shorten processing time for the solver. For the purposes of the demonstration, the discount rate for the planning horizon was set to 0, assuming all costs were stated in real terms. Because the calculations for the matrix are done before running the model, any discount rate could be used to adjust the present value of the costs and inserted in the coefficient matrix. A subset of this matrix is shown in Figure 16.

Alternative	Year 1	Year 2	Year 3	Year 4	Year 5
Lake 1	$ 34,655,253	$ 33,654,469	$ 32,615,147	$ 31,537,287	$ 30,420,889
Lake 2	$ 35,832,107	$ 34,767,004	$ 33,664,693	$ 32,525,173	$ 31,348,444
Exchange	$ 27,542,080	$ 27,861,587	$ 28,053,520	$ 28,117,880	$ 28,054,667
New Wells	$ 7,956,000	$ 7,624,500	$ 7,293,000	$ 6,961,500	$ 6,630,000
Recycled Water	$ 11,966,400	$ 11,467,800	$ 10,969,200	$ 10,470,600	$ 9,972,000
Dam & Reservoir	$ 14,470,219	$ 13,942,176	$ 13,407,621	$ 12,866,555	$ 12,318,978

Figure 16. Example Model Cost Coefficient Matrix

Figure 16 only shows the alternatives with fixed capacities. In order to demonstrate the ability of the model to handle continuous variables as well, the capacity of desalination (both with and without solar) was allowed to vary between 300 and 820 AFY. The annualized costs were then calculated based on the equations presented in Figures 13 and 14 in Chapter 9 and applied to the entire planning horizon. This approach added nonlinearities to the model, which significantly increased the solver processing time.

10.1.2 Constraints Specific to Utility

Other than the standard capacity constraints, the alternatives relating to the desalination and lake options were limited to choosing one variation. That is, the utility could not build both a desalination plant and a second desalination plant with solar. These constraints are shown below:

$$\sum_{i=1}^{n}\left(x_{iDesalination} + x_{iDesalinationSolar}\right) \leq 1 \qquad (20)$$

$$\sum_{i=1}^{n}\left(x_{iLakeRoute1} + x_{iLakeRoute2}\right) \leq 1 \qquad (21)$$

10.1.3 Baselining the Goals

With the performance measures set to make up the goals, the model was run to maximize goal achievement for each goal individually to set a baseline or best case scenario. The only goal constraints were that the other two goals must be nonnegative.

The model runs are shown in Table 13. The ***What's Best*** output reports are shown in Appendix B titled by their run number, e.g. *Run1.xls*.

Table 13. Model Results - Baselining Goals

Scenario	**Minimize Cost (Maximize Economic Goal Achievement) Run1.xls**	**Maximize Environmental Goal Achievement Run2.xls**	**Maximize Social Goal Achievement Run3.xls**
Variable Capacity (AFY)			
Desalination	300	311	788
Water Supply Alternative (year brought into service)			
Desalination	0	0	0
Desalination with Solar	22	5	1
Lake Route 1	0	0	0
Lake Route 2	0	1	0
Exchange of Rights	0	1	1
New Wells	9	0	1
Recycled Water	18	1	1
Dam & Reservoir	1	0	0
Goal Achievement			
Environmental		163.6 (set to 1.0)	
Economic	$26.2 M (set to 1.0)		
Social			162 (set to 1.0)
Present Value of Total Cost			
Cost	$26,240,611	$95,528,202	$89,485,837

After the three runs, the best case for each goal was normalized to 1.0. The worst case for the environmental and social goals were set to 0. The worst case (0 score) for economic goal achievement was calculated at a cost where the estimated average water bill would account for two percent of the median household income. That threshold was calculated to be reached when the incremental costs from new water supplies reached

$95,528,202. As you can see by Run 2 (Maximizing Environmental Goal Achievement), the affordability aspect of the economic goal became a binding constraint.

10.2 Balancing the Goals

After baselining, the balancing act between the three aspects of the goals could be modeled. Table 14 shows the results of the model runs under the initial scenario. The first model run (Run4.xls) focused on maximizing the minimum goal achievement for all three goals. Subsequent runs were made relaxing the constraints for the minimum goal achievement.

Table 14. Model Results - Balancing Goals

Scenario	**Maximize Minimum Goal Achievement Run4.xls**	**Relax Constraint to Minimum of 0.6 Run5.xls**	**Relax Constraint to Minimum of 0.5 Run6.xls**
Variable Capacity (AFY)			
Desalination	300	300	300
Water Supply Alternative (year brought into service)			
Desalination	0	0	0
Desalination with Solar	0	14	22
Lake Route 1	0	0	0
Lake Route 2	0	0	0
Exchange of Rights	1	0	0
New Wells	1	1	10
Recycled Water	1	1	1
Dam & Reservoir	21	2	1
Goal Achievement			
Environmental	0.66	0.60	0.50
Economic	0.66	0.73	0.88
Social	0.82	0.83	0.67
Present Value of Total Cost			
Cost	$49,974,880	$44,777,280	$34,385,311

The threshold for this maxi-min problem led to a balanced choice with minimum goal achievement of 0.66 at a cost of roughly $50 million, nearly double the lowest cost alternative identified in the baselining exercise. When relaxing the constraint by roughly 10 percent to a minimum threshold of 0.6, the choices changed dramatically, while the cost dropped by about 10 percent. Relaxing the constraint by about 25 percent to a minimum threshold of 0.5 led to a further shift in recommended alternatives and a cost reduction of over 30 percent. Figure 17 displays this information graphically and includes the lowest cost alternative and an additional model run with a 0.4 threshold.

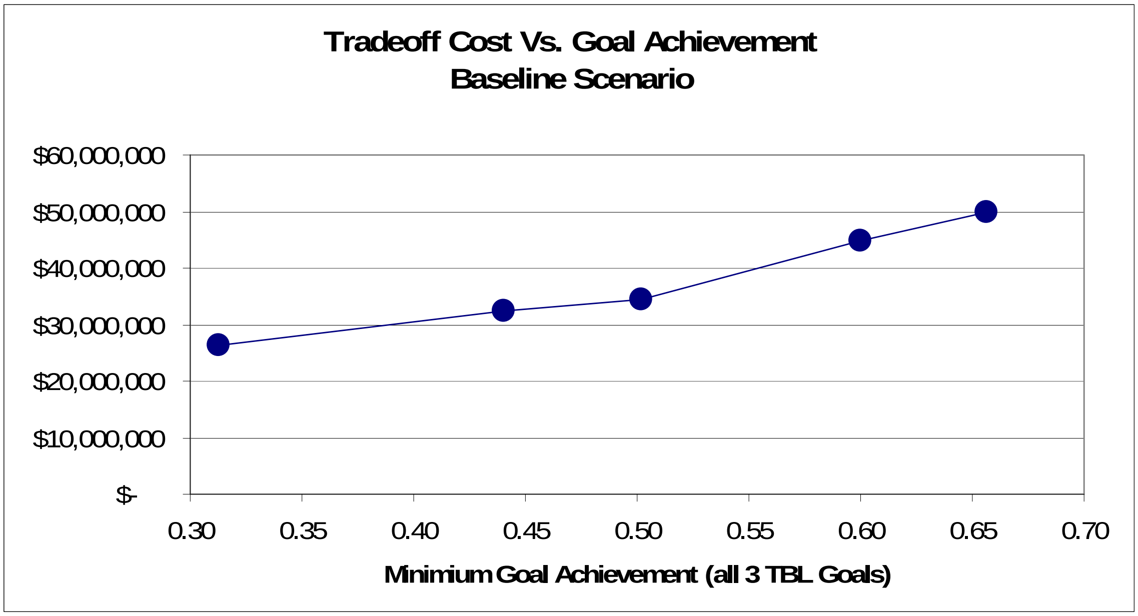

Figure 17. Tradeoff Curve: Goal Achievement Versus Cost

While the previous analysis was based on the highest achievement and moving away from that point, the tradeoff curve shows some interesting characteristics when looking at the data from the low cost end. At the lowest cost ($26 million) the minimum goal achievement is 0.31. Looking at the shape of the curve, it appears that the slope changes around 0.5 threshold, with a cost is $34 million. The decision makers could review this information and conclude that for a 31 percent cost premium ($34-$26 million) the utility could achieve over a 60 percent increase in environmental and social goal achievement (0.5-0.31). This type of analysis can be highly beneficial to utility planners in convincing the public, or even their own regulatory bodies, to incorporate the non-financial aspects of a plan into the decision process. The next two sections will present examples of sensitivity analyses that could be performed using the GP framework.

10.3 Goal Balancing After Policy Change

The previous example of using the model was a “brute force” approach: all alternatives were placed in the model without any additional forethought other than the goal definitions. Oftentimes when developing a plan, a utility may face regulatory and political constraints that can alter the decision making process. A scenario was developed where the goal definitions were left as originally constructed, but the alternatives were limited due to the following political decisions:

- Only the solar option of desalination will be considered – this may be due to a political or regulatory requirement that any additional power demands be obtained from renewable sources.

- Dam and Reservoir and New well options are excluded – the utility or political leaders determined that environmental impacts, property tax losses, or other factors make these options infeasible.

- Only Lake Route 2 will be considered - since the costs are similar, the benefits of the trout habitat are such that Route 2 will always be better than Route 1, a dominant solution.

By reducing the alternatives to four, the processing demands on the model are also lessened. Table 15 shows the outputs from the model runs under the policy change scenario and Figure 18 shows the resulting tradeoff curve.

Table 15. Model Results - Balancing Goals After Policy Change

Scenario	Minimize Cost (Maximize Economic Goal Achievement) Run8.xls	Maximize Minimum Goal Achievement Run9.xls	Relax Constraint to Minimum of 0.5 Run10.xls
Variable Capacity (AFY)			
Desalination	427	412	412
Water Supply Alternative (year brought into service)			
Desalination with Solar	9	13	13
Lake Route 2	0	0	0
Exchange of Rights	1	1	1
Recycled Water	21	3	9
Goal Achievement			
Environmental	0.44	0.62	0.55
Economic	0.68	0.62	0.66
Social	0.38	0.62	0.53
Present Value of Total Cost			
Cost	$48,666,780	$52,569,343	$49,577,743

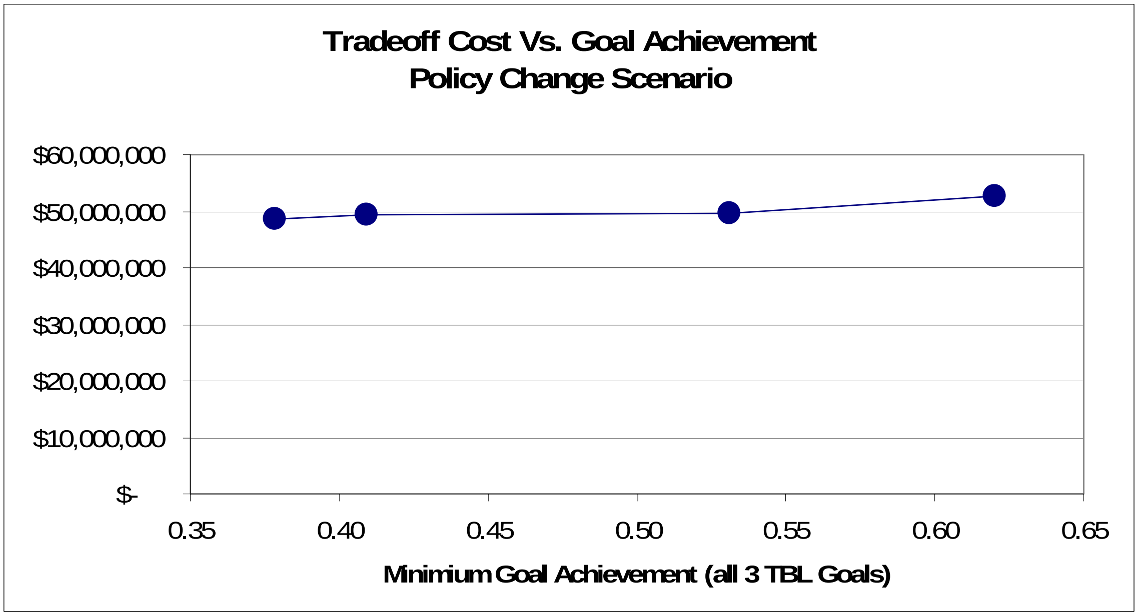

Figure 18. Tradeoff Curve: Goal Achievement Versus Cost for Policy Change Scenario

With the hypothetical political constraints in this scenario, the lowest cost alternative is nearly $49 million, with a minimum goal achievement threshold of 0.38. Under these conditions, the model shows that for an 8 percent cost increase, the minimum goal achievement can increase 64 percent. This is due to the fact that when the recycled water option is moved forward from year 21 to year 3, the environmental goal benefits dramatically increase on the use of recycled water measure, but costs go up only slightly in the balanced recommendation.

10.4 Weighting the Component Measures

When evaluating the baseline scenario results, it became clear that the nature of the goal definitions were pushing decisions forward in the planning horizon in order to accrue "credit" towards the environmental and social goals. Even if an alternative had a low score (say 0.1 of the 1.0 scale), the total would increase if the alternative was recommended to be placed in service. Two changes were made to address the issues. First, a constraint was added to limit the built capacity to the maximum demand for the planning horizon plus an arbitrary factor of 33 percent for reserve capacity. Secondly, the goal component measures were weighted. Table 16 shows the weights of each component for the social and environmental goals.

Table 16. Goal Component Weighting Schema

Relative Weight Within the Goal (Higher is More Important)	Environmental Goal Component	Social Goal Component
16	Use of Recycled Water	
9	Environmental Issues	Reliability
4	Solar Power	Institutional Issues
1	Water Quality	Permitting

A weighting scale using square numbers (1, 4, 9, and 16) was arbitrarily chosen. Reliability was ranked the highest for social goal component due to the strength of the reliability factors in the Social Indicator's targeted survey responses discussed in Chapter 6. The balance of the measures were ranked based on best professional judgment of the researcher and solely used for model demonstration.

After the weighting, the maximum goal achievement for both environmental and social goals were re-baselined (Run12.xls and Run13.xls in Appendix B). Table 17 shows the results of the weighted runs in comparison to the unweighted balanced approach.

Table 17. Model Results - Balancing Goals With Weighting

Scenario	Maximize Minimum Goal Achievement *Baseline - Unweighted* Run4.xls	Maximize Minimum Goal Achievement Weighted Run14.xls	Relax Constraint to Minimum of 0.6 Weighted Run15.xls
Variable Capacity (AFY)			
Desalination	300	318	300
Water Supply Alternative (year brought into service)			
Desalination	0	0	0
Desalination with Solar	0	7	20
Lake Route 1	0	0	0
Lake Route 2	0	0	0
Exchange of Rights	1	0	0
New Wells	1	19	12
Recycled Water	1	1	1
Dam & Reservoir	21	1	1
Goal Achievement			
Environmental	0.66	0.70	0.60
Economic	0.66	0.70	0.86
Social	0.82	0.70	0.61
Present Value of Total Cost			
Cost	$49,974,880	$46,796,181	$35,706,439

Weighting the goals provided a cost reduction from $50 million to $47 million on the balanced approach and brought the solar powered desalination plant into the recommended set of alternatives. Similar to the other alternatives, relaxing the achievement constraint to 0.6 (a 14 percent decrease) yielded a cost savings of over $11 million (24 percent). Looking at the recommended set of alternatives under each of the scenarios demonstrates that wide swings in the solution sets can occur at similar costs, depending on the underlying definitions and weighting of the goals.

11 SUMMARY AND CONCLUSIONS

11.1 Hypothesis and Research Questions

As posited in Chapter 3, the hypothesis for this research is that an integrated water resources plan can achieve balance between the three components of sustainability (economic/financial, social, and environmental). Using a publicly available water supply master plan, a goal program was developed that provided feasible solutions and insight into the problem as proof of concept.

The demonstration also addressed the subsidiary research questions discussed in Chapter 3 as follows:

1. ***Can the three primary components of sustainability be equally weighted and still yield feasible solutions?*** Cost concerns are a fact of life and the economic aspects of sustainability will probably always be the first concern for decision makers. However, the GP demonstrated that solutions can be developed that can balance the three aspects of the TBL. At the very least, the tradeoff curve developed through the GP can provide information to aid a decision maker in identifying the most politically and technically feasible set of alternatives; that is, how much environmental and social goal progress can the decision maker achieve at an acceptable cost.

2. ***What data are needed by the decision makers in order to successfully analyze social and environmental components?*** Potential performance measures for each of the three goals were identified based on the literature. In addition, a group of industry experts was polled regarding social sustainability indicators, the most difficult measures to obtain. The targeted survey responses led to recommendations of a set of measures that can aid decision makers. Finally, the demonstration scenario showed that utilities can obtain the data needed to successfully analyze the non-financial components.

3. ***How can the inherently qualitative aspects of environmental impact be quantified?*** The research demonstrated that measures such as wastewater reuse, amount of power from renewable energy and carbon footprint can be used. In addition, the utility data used in the proof of concept demonstrated categorical variables can be used to quantify qualitative aspects of environmental measures such as habitat for endangered or threatened species of flora and fauna.

4. ***How can the inherently qualitative aspects of social impact be quantified?*** Upon embarking on this research, there were concerns that the measures needed to evaluate the social aspect of the TBL would be exceptionally difficult to incorporate into a mathematical model, due to the lack of industry consensus regarding the social measures, as well as the qualitative nature of the social component in general. This work has demonstrated that industry decision makers can identify consistent and useful social indicators that can be integrated into a decision analysis methodology.

The research demonstrated that measures covering topics such as affordability and reliability can be implemented in a quantitative fashion. In addition, the utility data used in the proof of concept demonstrated categorical variables can be used to quantify qualitative aspects of social measures, such as archeological sites for Native American culture. However, social sustainability remains difficult to quantify. The targeted expert survey performed for this research was limited to obtaining the viewpoint of decision makers and policy influencers in the water industry. The results may have been different if the survey population was the general public.

5. ***Can optimization techniques, which are prevalent in facility and network design and inter-basin planning, be implemented at the municipal planning level?*** Goal Programming using non-linear and integer programming solvers in MS Excel was able to generate feasible solutions and tradeoff analyses. The demonstration served as a proof of concept that the goal programming technique could be implemented using the data readily available at a water utility.

6. ***Can generic goals be set up to minimize the need for subjective weighting?*** The demonstration project was originally developed with unweighted components within each goal. This led to the development of a composite goal where items that best professional judgment would claim were not of equal importance were given the same contribution to the final goal. While the overall goals can be balanced, the components within the goal would appear to provide more valuable insight by weighting the measures within the goals. Weighting the individual measures within

each goal can enable the goals to still be balanced while the more important measures within each goal can outweigh the less important constituents of the goal.

11.2 Opportunities for Future Research

As the sustainability movement pushes forward, there will be numerous opportunities for related research. A few opportunities are discussed below.

11.2.1 Refining Goals

Many of the measures in the demonstration were based on categorical variables rated from 1 to 5. Better enumerating, weighting, and quantifying these measures would provide more insight into the problem. For example, the Water Quality measure in the environmental goal was rated 1 for desalination. A more robust approach might be to have the model consider blending reverse osmosis water with groundwater to provide better quality water. Instead of a 1-5 scale, perhaps a component such as total dissolved solids (TDS) could be used. If RO water has TDS of 485 mg/l and groundwater has TDS of 10 mg/l, the measure may be directly calculated instead of categorized.

11.2.2 Incorporating Other Related Industries

The demonstration scenario encompassed the wastewater aspect of total water management through the availability of water recycling as an alternative. Including wastewater and stormwater facets into the scope of the model offers promise for more thorough analysis of the issues facing integrated solutions.

11.2.3 Incorporating Uncertainty

Perhaps the largest opportunity for future research is in the incorporation of uncertainty into the model. The industry standard for evaluating resource combinations is through enumeration of scenarios or sequences (Means et. al, 2005). The use of optimization techniques in this research seeks to provide a more comprehensive approach to evaluating these alternative combinations without enumerating all possible solution sets. Correspondingly, the industry state of the art for incorporating uncertainty into evaluations is also based on discrete scenarios. Scenario planning has been the basis for industry workshops and publications since 2000. As with deterministic problem solving, advanced stochastic methods have been used at the basin-level planning and municipal design and operation, but little has been applied to municipal planning.

Stochastic goal programming through the use of chance constrained optimization could be used. Alternatively, a complementary model (as opposed to the chance constrained option which integrates uncertainty into the model) using Monte Carlo Simulation to further evaluate "optimal" solution may be developed.

11.3 Conclusion

The largest uncertainty at the beginning of the research was whether an approach to attempt to balance the three components of the TBL would even be feasible. The research has developed a methodology to that can successfully generate feasible solutions while balancing all three components. Furthermore, the research showed that the methodology could use existing data and tools to develop tradeoffs between the various aspects of the TBL. The methodology has the potential to provide increased visibility to cost, societal and environmental issues for to the decision makers in order to enhance the decision analysis of water supply strategies. Papers and presentations discussing various elements of this research have been published (or accepted for publication) in the proceedings of the following conferences:

Liner, Barry and deMonsabert, Sharon. (2009). Social Sustainability Measures for Total Water Management. Proceedings of Engineering Sustainability 2009. April 21, 2009. Pittsburgh, PA.

Liner, Barry and deMonsabert, Sharon. (2009). Sustainability Goals for Total Water Management. Proceedings of American Water Works Association Annual Conference – University Forum. June 16, 2009. San Diego, CA.

deMonsabert, Sharon, Maas, Carol, Bakshi, Ali, and Liner, Barry. (2009) Incorporating Energy Impacts Into Water Supply and Wastewater Management. ACEEE Summer Study. July 28-31, 2009. Niagara Falls, NY.

Liner, Barry and deMonsabert, Sharon. (2009). Sustainability Goal Programming for Total Water Management. Proceedings of WEFTEC 2009. October 13, 2009. Orlando, FL.

APPENDIX A: SURVEY FORM

Dear Respondent,

I am inviting you participate in a research project to study sustainability in total water management. Along with this letter is a short questionnaire that asks a variety of questions about performance measures for social sustainability. I am asking you to look over the questionnaire and, if you choose to do so, complete it and send it back to me. It should take you less than fifteen minutes to complete.

The answers to the survey will be used to establish a baseline weighting for the sustainability measures in a goal programming model to attempt to balance economic, environmental, and social aspects of sustainability in water supply. I plan to share my results by presenting them at the Engineering Sustainability 2009 Conference, AWWA ACE, and WEFTEC, as well as incorporating the results into my doctoral dissertation.

I do not know of any risks to you if you decide to participate in this survey. All results will be presented in aggregate and no data will be directly related to an individual respondent. I promise not to share any information that identifies you with anyone outside my research group which consists of me and my Ph.D. Committee.

The survey should take you about fifteen minutes to complete. I hope you will take the time to complete this questionnaire and return it. Your participation is voluntary. I will be happy to send you a copy of my public presentations if you desire – there is a check box on the survey form to indicate your preferences.

If you have any questions or concerns about completing the questionnaire or about being in this study, you may contact me at bliner@gmu.edu or 703-727-8781. The Human Subjects Research Board (HSRB) at George Mason University has approved this study.

I would greatly appreciate if you would sign the informed consent form and complete the survey and return them to me at your earliest convenience. I thank you in advance for your participation.

Sincerely,

Barry L. Liner, PE
Ph.D. Candidate

Approval for the use
of this document
EXPIRES
FEB 19 2010
Protocol # 6167
George Mason University

Goal Programming for Sustainability in Total Water Management

INFORMED CONSENT FORM

RESEARCH PROCEDURES
This research is being conducted to attempt to help identify potential social performance measures (equity, security, affordability, job creation, etc.) for use in water supply planning. If you agree to participate, you will be asked to complete a brief survey about potential data availability and usefulness for candidate social sustainability performance measures. The answers to the survey will be used to establish a baseline weighting for the sustainability measures in the goal programming model. It is expected that completion of the survey will take approximately fifteen minutes.

RISKS
There are no foreseeable risks for participating in this research.

BENEFITS
There are no benefits to you as a participant other than to further research in the area of sustainability in water resources.

CONFIDENTIALITY
The data in this study will be confidential. The results of this survey will be integrated into the goal programming model and will be included in a graduate dissertation, presented at conferences, and may also be published in journal articles. All results will be presented in aggregate and no data will be directly related to a respondent.

PARTICIPATION
Your participation is voluntary, and you may withdraw from the study at any time and for any reason. If you decide not to participate or if you withdraw from the study, there is no penalty or loss of benefits to which you are otherwise entitled. There are no costs to you or any other party.

CONTACT
This research is being conducted Barry Liner, a doctoral student at George Mason University's Civil, Environmental, and Infrastructure Engineering (CEIE) Department. He may be reached at 703-727-8781 for questions or to report a research-related problem. Dr. Sharon deMonsabert, Assistant Professor in CEIE, is directing the project and may be reached at 703-993-1747. You may contact the George Mason University Office of Research Subject Protections at 703-993-4121 if you have questions or comments regarding your rights as a participant in the research.

This research has been reviewed according to George Mason University procedures governing your participation in this research.

CONSENT
I have read this form and agree to participate in this study.

____
Name

____
Date of Signature

Approval for the use
of this document
EXPIRES
FEB 19 2010
Protocol # 6167
George Mason University

Social Indicator Survey for Sustainable Water Usage

Respondent: NAME

☐ I would like to receive a copy of the public presentations that result from this research.

Background

This research seeks to apply an optimization framework to sustainability aspects of total water management. With the Triple Bottom Line (TBL) of Sustainability, total water management efforts must analyze alternatives to address the potentially conflicting goals of economics (financial), environmental, and social issues.

Performance measures for each of the three goals (economic, environmental, and social) are the core building blocks to enable analysis of total water management plans. Generally, economic goals are well understood and defined. These may include commodity rates, return on assets, debt level, etc. Over the past decade, environmental goals have been developing enhanced understanding and usage. Measures such as carbon footprint, area of wetland restoration and wastewater reuse are in use. However, the American Water Works Association Research Foundation published study on TBL (2007), recognized that the social measures were lacking.

This survey is an attempt to help identify potential social performance measures (equity, security, affordability, job creation, etc.) for use in water supply planning. A small focus group of approximately a dozen utility managers and other industry experts is being surveyed to determine the efficacy and usability of the candidate social measures.

The candidate indicators are meant to be used within a utility to help make decisions on water supply alternatives, not to compare between utilities.

For any questions, please contact bliner@gmu.edu.

Questions about Usability & Data Availability

Indicator 1	Affordability: Average Water Bill / Median Household Income				
Source/Rationale	Indicator B10 in AWWA TBL Reporting Guide. Also in SEEAW				
Usability of Measure	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives					
Data Availability For Measure Calculation	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship					
Comments					

Indicator 2	Affordability: (Water Bill for non-discretionary water use) / Median Household Income				
Source/Rationale	Modification of Indicator 1 to account for only non-discretionary water usage. 6 kgal/month is the value AWWARF uses in TBL Reporting Guide				
Usability of Measure	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives					
Data Availability For Measure Calculation	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship					
Comments					

Indicator 3	Job Creation: # of Jobs Created At Utility				
Source/Rationale	Indicator B2 in AWWA TBL Reporting Guide				
Usability of Measure	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives					
Data Availability For Measure Calculation	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship					
Comments					

Indicator 4	Job Creation: # of Jobs Made Possible In Community
Source/Rationale	Modification of Indicator 3 to account for new industry or development made possible by utility expansion or upgrade of service

Usability of Measure	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives					

Data Availability For Measure Calculation	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship					

Comments	

Indicator 5	Security/Reliability: Percent of Minimum Demand Utility Can Supply When Largest Water Treatment Plant is Non-Functional
Source/Rationale	CIPAC Water Security Metrics, derived from NDWAC 14 Features.

Usability of Measure	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives					

Data Availability For Measure Calculation	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship					

Comments	

Indicator 6	Security/Reliability: Expected Duration to Meet Minimum Demand on Backup Power After Power Loss
Source/Rationale	CIPAC Water Security Metrics, derived from NDWAC 14 Features

Usability of Measure	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives					

Data Availability For Measure Calculation	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship					

Comments	

Indicator 7	Security/Reliability: Population within "X distance" of Cl_2 Storage					
Source/Rationale	CIPAC Water Security Metrics, derived from NDWAC 14 Features. Distance as appropriate for each individual organization					
Usability of Measure		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives						
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives						
Data Availability For Measure Calculation		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship						
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship						
Comments						

Indicator 8	Security/Reliability: Customer * Hours of Service Lost Due To Water Main Breaks					
Source/Rationale	Indicator B11 in AWWA TBL Reporting Guide. Time period as applicable (per year, month, etc.). Service loss defined at utility (low pressure,					
Usability of Measure		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives						
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives						
Data Availability For Measure Calculation		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship						
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship						
Comments						

Indicator 9	Security/Reliability: Customer * Hours of Service Lost Due To Sewer Collapses					
Source/Rationale	Indicator B11 in AWWA TBL Reporting Guide. Time period as applicable (per year, month, etc.)					
Usability of Measure		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives						
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives						
Data Availability For Measure Calculation		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship						
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship						
Comments						

Indicator 10	Outreach/Education: # People Participating in Educational Programs Provided By Utility					
Source/Rationale	Indicator B7 in AWWA TBL Reporting Guide. Also in GRI					
Usability of Measure		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives						
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives						
Data Availability For Measure Calculation		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship						
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship						
Comments						

Indicator 11	Outreach/Education: Percent of Impacted Population Notified of Public Comment Opportunities					
Source/Rationale	Indicator B7 in AWWA TBL Reporting Guide. Also in GRI. Alternatives might be # people notified, or # people attending hearings.					
Usability of Measure		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives						
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives						
Data Availability For Measure Calculation		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship						
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship						
Comments						

Indicator 12	Public Recreation: Area Created for Parks and Green space					
Source/Rationale	Parkland and green space created through projects or made possible by projects. From ISEW					
Usability of Measure		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives						
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives						
Data Availability For Measure Calculation		Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship						
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship						
Comments						

Indicator 13

Public Recreation: # People Using Water for Recreation

Source/Rationale: Boating, fishing, etc. on reservoir or additional stream flow. From ISEW

Usability of Measure	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives					

Data Availability For Measure Calculation	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship					

Comments

Indicator 14

Environmental Justice: Benefits to Distressed Communities / Costs borne by Distressed Communities

Source/Rationale: ISEW, related to Indicator B5 in AWWA TBL Reporting Guide. Benefit definition as appropriate by organization

Usability of Measure	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives					

Data Availability For Measure Calculation	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship					

Comments

Indicator 15

Public Health: #People with Reduced Exposure to Contaminants

Source/Rationale: Indicator B6 in AWWA TBL Reporting Guide. Better indicator would be reduced cases of waterborne illness or reduced cancer cases due to dose response curve, but data is assumed to be too subjective or difficult to obtain

Usability of Measure	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
MY UTILITY MANAGMENT would potentially be able to use this measure to assist in making decisions about water supply alternatives					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would potentially be able to use this measure to assist in making decisions about water supply alternatives					

Data Availability For Measure Calculation	Strongly Disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly Agree (5)
AT MY UTILITY, I would be able to gather the data, or develop reasonable estimates, required to calculate this measure without undue hardship					
MANAGERS AT OTHER WATER/WASTEWATER UTILITIES would be able to gather the data, or develop reasonable estimates, required to calculate measure without undue hardship					

Comments

Ranking

Please place the indicators into three groups of five. If you had to choose 5 social indicators of potential use to the water industry, which five would they be (Please label these Group A)? After group A, which would be your next five, if you had to choose five more (Group B).

Group	Measure
	Average Water Bill / Median Household Income
	Water Bill for 6 kgal/month / Median Household Income
	# of Jobs Created At Utility By Project
	# of Jobs Created In Community By Project
	Percent of Minimum Demand Utility Can Supply When Largest Water Treatment Plant is Non-Functional
	Expected Duration to Meet Minimum Demand on Backup Power After Power Loss
	Population within X distance of Chlorine Storage
	Customer – Hours of Service Lost Due To Water Main Breaks
	Customer – Hours of Service Lost Due To Sewer Collapses
	# People Participating in Educational Programs Provided By Utility
	Percent of Impacted Population Notified of Public Comment Opportunities
	Area Created for Parks and Greenspace
	# People Using Water Resources for Recreation
	Benefits to Distressed Communities / Costs borne by Distressed Communities
	# Population with Reduced Exposure to Contaminants

Are there any other social indicators that you think might be useful for helping water and wastewater utilities to improve sustainability?

References

- GRI, Global Reporting Initiative
  - http://www.globalreporting.org/Home
- ISEW, Index of Sustainable Economic Welfare (ISEW)
  - http://www.foe.co.uk/community/tools/isew/
- System of Environmental-Economic Accounting for Water
  - http://unstats.un.org/unsd/envaccounting/seeaw.asp
- Triple Bottom Line Reporting of Sustainable Water Utility
  - http://www.awwa.org/bookstore/productDetail.cfm?ItemNumber=31055

APPENDIX B: MODEL RUNS

Run1.xls

```
What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 13, 2009             02:26 AM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                          1768
  Variables                          723
  Adjustables                        193              2000
  Constraints                         32              1000
  Integers/Binaries                0/192               200
  Nonlinears                          98               200
  Coefficients                      1724

  Minimum coefficient value:        1  on Sheet1!B12
  Minimum coefficient in formula:   Sheet1!B12
  Maximum coefficient value:        35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:   Sheet1!D42

MODEL TYPE:             Mixed Integer / Nonlinear

SOLUTION STATUS:        LOCALLY OPTIMAL

OPTIMALITY CONDITION:   SATISFIED

OBJECTIVE VALUE:        26240610.666667

DIRECTION:              Minimize

SOLVER TYPE:            Branch-and-Bound

TRIES:                  1549300

INFEASIBILITY:          1.862645149231e-009

BEST OBJECTIVE BOUND:   26240610.666667

STEPS:                  4561

ACTIVE:                 0

SOLUTION TIME:          4 Hours 13 Minutes 51 Seconds
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Run2.xls

```
What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 14, 2009             09:33 PM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                          1784
  Variables                          948
  Adjustables                        193              2000
  Constraints                         36              1000
  Integers/Binaries                  0/192             200
  Nonlinears                         100               200
  Coefficients                      2373

  Minimum coefficient value:        1.4432598795438e-008  on Sheet1!C51
  Minimum coefficient in formula:   Sheet1!C82
  Maximum coefficient value:        35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:   Sheet1!D46

MODEL TYPE:             Mixed Integer / Nonlinear

SOLUTION STATUS:        LOCALLY OPTIMAL

OPTIMALITY CONDITION:   SATISFIED

OBJECTIVE VALUE:        163.58147754824

DIRECTION:              Maximize

SOLVER TYPE:            Branch-and-Bound

TRIES:                  628792

INFEASIBILITY:          1.6376376152039e-005

BEST OBJECTIVE BOUND:   163.58147754824

STEPS:                  527

ACTIVE:                 0

SOLUTION TIME:          1 Hours 10 Minutes 17 Seconds
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Run3.xls

```
What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 20, 2009              04:35 PM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                         1784
  Variables                         948
  Adjustables                       193              2000
  Constraints                        36              1000
  Integers/Binaries                 0/192             200
  Nonlinears                        100               200
  Coefficients                     2373

  Minimum coefficient value:       1.4432598795438e-008  on Sheet1!C51
  Minimum coefficient in formula:  Sheet1!C82
  Maximum coefficient value:       35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:  Sheet1!D46

MODEL TYPE:              Mixed Integer / Nonlinear

SOLUTION STATUS:         LOCALLY OPTIMAL

OPTIMALITY CONDITION:    SATISFIED

OBJECTIVE VALUE:         162

DIRECTION:               Maximize

SOLVER TYPE:             Branch-and-Bound

TRIES:                   1813821

INFEASIBILITY:           7.4505805969238e-009

BEST OBJECTIVE BOUND:    162

STEPS:                   1361

ACTIVE:                  0

SOLUTION TIME:           2 Hours  4 Minutes 54 Seconds
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Run4.xls

```
What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 15, 2009            12:12 AM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                         1780
  Variables                         952
  Adjustables                       194              2000
  Constraints                        36              1000
  Integers/Binaries                 0/192             200
  Nonlinears                        100               200
  Coefficients                     2382

  Minimum coefficient value:       1.4432598795438e-008  on Sheet1!C51
  Minimum coefficient in formula:  Sheet1!C82
  Maximum coefficient value:       35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:  Sheet1!D46

MODEL TYPE:              Mixed Integer / Nonlinear

SOLUTION STATUS:         LOCALLY OPTIMAL

OPTIMALITY CONDITION:    SATISFIED

OBJECTIVE VALUE:         0.65615193381424

DIRECTION:               Maximize

SOLVER TYPE:             Branch-and-Bound

TRIES:                   373461

INFEASIBILITY:           2.2351741790771e-008

BEST OBJECTIVE BOUND:    0.65615193381424

STEPS:                   282

ACTIVE:                  0

SOLUTION TIME:           0 Hours 35 Minutes  5 Seconds
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Run5.xls

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What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 15, 2009             12:42 PM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                          1785
  Variables                          946
  Adjustables                        193              2000
  Constraints                         35              1000
  Integers/Binaries                  0/192             200
  Nonlinears                         100               200
  Coefficients                      2369

  Minimum coefficient value:        0.001219512195122  on Sheet1!A12
  Minimum coefficient in formula:   Sheet1!I72
  Maximum coefficient value:        35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:   Sheet1!D46

MODEL TYPE:              Mixed Integer / Nonlinear

SOLUTION STATUS:         LOCALLY OPTIMAL

OPTIMALITY CONDITION:    SATISFIED

OBJECTIVE VALUE:         44777279.777778

DIRECTION:               Minimize

SOLVER TYPE:             Branch-and-Bound

TRIES:                   2586862

INFEASIBILITY:           1.862645149231e-009

BEST OBJECTIVE BOUND:    44777279.777778

STEPS:                   2374

ACTIVE:                  0

SOLUTION TIME:           3 Hours 47 Minutes 54 Seconds
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Run6.xls

```
What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 15, 2009             09:38 PM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                         1785
  Variables                         946
  Adjustables                       193            2000
  Constraints                        35            1000
  Integers/Binaries                 0/192           200
  Nonlinears                        100             200
  Coefficients                     2369

  Minimum coefficient value:       0.001219512195122  on Sheet1!A12
  Minimum coefficient in formula:  Sheet1!I72
  Maximum coefficient value:       35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:  Sheet1!D46

MODEL TYPE:             Mixed Integer / Nonlinear

SOLUTION STATUS:        LOCALLY OPTIMAL

OPTIMALITY CONDITION:   SATISFIED

OBJECTIVE VALUE:        34385310.666667

DIRECTION:              Minimize

SOLVER TYPE:            Branch-and-Bound

TRIES:                  1568270

INFEASIBILITY:          6.3131665228866e-008

BEST OBJECTIVE BOUND:   34385310.666667

STEPS:                  2000

ACTIVE:                 0

SOLUTION TIME:          2 Hours 22 Minutes 11 Seconds

ERROR / WARNING MESSAGES:
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Run8.xls

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What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Apr 01, 2009              08:57 AM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                          2265
  Variables                          479
  Adjustables                         97             2000
  Constraints                         33             1000
  Integers/Binaries                 0/96              200
  Nonlinears                          49              200
  Coefficients                      1092

  Minimum coefficient value:        1  on Sheet1!B12
  Minimum coefficient in formula:   Sheet1!B12
  Maximum coefficient value:        35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:   Sheet1!D46

MODEL TYPE:             Mixed Integer / Nonlinear

SOLUTION STATUS:        LOCALLY OPTIMAL

OPTIMALITY CONDITION:   SATISFIED

OBJECTIVE VALUE:        48666780.088939

DIRECTION:              Minimize

SOLVER TYPE:            Branch-and-Bound

TRIES:                  474043

INFEASIBILITY:          0.00022576749324799

BEST OBJECTIVE BOUND:   48666780.088939

STEPS:                  535

ACTIVE:                 0

SOLUTION TIME:          0 Hours 43 Minutes 31 Seconds
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Run9.xls

```
What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 16, 2009             01:52 AM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                          2138
  Variables                          598
  Adjustables                         98             2000
  Constraints                         36             1000
  Integers/Binaries                 0/96              200
  Nonlinears                          51              200
  Coefficients                      1430

  Minimum coefficient value:        1.4432598795438e-008  on Sheet1!C51
  Minimum coefficient in formula:   Sheet1!C82
  Maximum coefficient value:        35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:   Sheet1!D46

MODEL TYPE:             Mixed Integer / Nonlinear

SOLUTION STATUS:        LOCALLY OPTIMAL

OPTIMALITY CONDITION:   SATISFIED

OBJECTIVE VALUE:        0.62000796655284

DIRECTION:              Maximize

SOLVER TYPE:            Branch-and-Bound

TRIES:                  752821

INFEASIBILITY:          0.0001506470143795

BEST OBJECTIVE BOUND:   0.62000796655284

STEPS:                  521

ACTIVE:                 0

SOLUTION TIME:          0 Hours 58 Minutes 31 Seconds

ERROR / WARNING MESSAGES:
```

Run10.xls

```
What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 16, 2009              11:05 AM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                          2143
  Variables                          592
  Adjustables                         97             2000
  Constraints                         35             1000
  Integers/Binaries                 0/96              200
  Nonlinears                          51              200
  Coefficients                      1417

  Minimum coefficient value:        0.001219512195122  on Sheet1!A12
  Minimum coefficient in formula:   Sheet1!I72
  Maximum coefficient value:        35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:   Sheet1!D46

MODEL TYPE:             Mixed Integer / Nonlinear

SOLUTION STATUS:        LOCALLY OPTIMAL

OPTIMALITY CONDITION:   SATISFIED

OBJECTIVE VALUE:        49577743.199316

DIRECTION:              Minimize

SOLVER TYPE:            Branch-and-Bound

TRIES:                  2010739

INFEASIBILITY:          0.00031648576259613

BEST OBJECTIVE BOUND:   49577743.199316

STEPS:                  2997

ACTIVE:                 0

SOLUTION TIME:          3 Hours  9 Minutes 51 Seconds
```

Run11.xls

```
What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 17, 2009              12:25 AM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                         2143
  Variables                         592
  Adjustables                        97             2000
  Constraints                        35             1000
  Integers/Binaries                 0/96             200
  Nonlinears                         51              200
  Coefficients                     1417

  Minimum coefficient value:       0.001219512195122  on Sheet1!A12
  Minimum coefficient in formula:  Sheet1!I72
  Maximum coefficient value:       35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:  Sheet1!D46

MODEL TYPE:             Mixed Integer / Nonlinear

SOLUTION STATUS:        LOCALLY OPTIMAL

OPTIMALITY CONDITION:   SATISFIED

OBJECTIVE VALUE:        49277764.266716

DIRECTION:              Minimize

SOLVER TYPE:            Branch-and-Bound

TRIES:                  3376128

INFEASIBILITY:          0.00017224997282028

BEST OBJECTIVE BOUND:   49277764.266716

STEPS:                  6780

ACTIVE:                 0

SOLUTION TIME:          5 Hours 28 Minutes  6 Seconds
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Run12.xls

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What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 17, 2009             08:31 AM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                          1808
  Variables                          937
  Adjustables                        193             2000
  Constraints                         34             1000
  Integers/Binaries                  0/192            200
  Nonlinears                         100              200
  Coefficients                      2344

  Minimum coefficient value:        1.4432598795438e-008  on Sheet1!C51
  Minimum coefficient in formula:   Sheet1!C82
  Maximum coefficient value:        35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:   Sheet1!D46

MODEL TYPE:              Mixed Integer / Nonlinear

SOLUTION STATUS:         LOCALLY OPTIMAL

OPTIMALITY CONDITION:    SATISFIED

OBJECTIVE VALUE:         1293.7165724587

DIRECTION:               Maximize

SOLVER TYPE:             Branch-and-Bound

TRIES:                   273335

INFEASIBILITY:           0.36261317506433

BEST OBJECTIVE BOUND:    1293.7165724587

STEPS:                   179

ACTIVE:                  1

SOLUTION TIME:           0 Hours 23 Minutes 58 Seconds
```

Run13.xls

```
What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 17, 2009             09:18 AM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                          1809
  Variables                          936
  Adjustables                        193              2000
  Constraints                         34              1000
  Integers/Binaries                  0/192             200
  Nonlinears                          98               200
  Coefficients                      2341

  Minimum coefficient value:        1.4432598795438e-008  on Sheet1!C51
  Minimum coefficient in formula:   Sheet1!C82
  Maximum coefficient value:        35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:   Sheet1!D46

MODEL TYPE:             Mixed Integer / Nonlinear

SOLUTION STATUS:        LOCALLY OPTIMAL

OPTIMALITY CONDITION:   SATISFIED

OBJECTIVE VALUE:        874

DIRECTION:              Maximize

SOLVER TYPE:            Branch-and-Bound

TRIES:                  724458

INFEASIBILITY:          0.0032520331442356

BEST OBJECTIVE BOUND:   874

STEPS:                  324

ACTIVE:                 0

SOLUTION TIME:          0 Hours 43 Minutes 39 Seconds
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Run14.xls

```
What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 17, 2009             12:20 PM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                          1798
  Variables                          952
  Adjustables                        194              2000
  Constraints                         36              1000
  Integers/Binaries                  0/192             200
  Nonlinears                         100               200
  Coefficients                      2382

  Minimum coefficient value:        1.4432598795438e-008  on Sheet1!C51
  Minimum coefficient in formula:   Sheet1!C82
  Maximum coefficient value:        35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:   Sheet1!D46

MODEL TYPE:             Mixed Integer / Nonlinear

SOLUTION STATUS:        LOCALLY OPTIMAL

OPTIMALITY CONDITION:   SATISFIED

OBJECTIVE VALUE:        0.70332969853256

DIRECTION:              Maximize

SOLVER TYPE:            Branch-and-Bound

TRIES:                  2781485

INFEASIBILITY:          0.00030425190925598

BEST OBJECTIVE BOUND:   0.70332969853256

STEPS:                  2337

ACTIVE:                 0

SOLUTION TIME:          2 Hours 57 Minutes 35 Seconds
```

Run15.xls

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What'sBest!® 9.0.3.6 (Feb 11, 2009) - Library 5.0.1.363 - Status Report -

DATE GENERATED:          Mar 17, 2009             01:26 PM


MODEL INFORMATION:

  CLASSIFICATION DATA            Current   Capacity Limits
  --------------------------------------------------------
  Numerics                         1803
  Variables                         946
  Adjustables                       193            2000
  Constraints                        35            1000
  Integers/Binaries                 0/192           200
  Nonlinears                        100             200
  Coefficients                     2369

  Minimum coefficient value:       0.00077296683157103  on Sheet1!H78
  Minimum coefficient in formula:  Sheet1!C81
  Maximum coefficient value:       35832106.666667  on Sheet1!D6
  Maximum coefficient in formula:  Sheet1!D46

MODEL TYPE:             Mixed Integer / Nonlinear

SOLUTION STATUS:        LOCALLY OPTIMAL

OPTIMALITY CONDITION:   SATISFIED

OBJECTIVE VALUE:        35706438.666667

DIRECTION:              Minimize

SOLVER TYPE:            Branch-and-Bound

TRIES:                  736659

INFEASIBILITY:          1.862645149231e-009

BEST OBJECTIVE BOUND:   35706438.666667

STEPS:                  361

ACTIVE:                 0

SOLUTION TIME:          0 Hours 55 Minutes  3 Seconds
```

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CURRICULUM VITAE

Barry Liner graduated from First Colonial High School, Virginia Beach, Virginia in 1985. He received his Bachelor of Arts from Virginia Tech in 1990. He has worked in the water resources field since that time and received a Master of Science in Urban Systems Engineering with a concentration in Environmental Systems from George Mason University in 1996.