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EVALUATION OF NITRATE TREATMENT METHODS UNDER UNCERTAINTY*

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ABSTRACT

Many small towns in the United States currently are faced with high nitrate levels in their drinking water and limited resources to address this issue. There are many methods of removing nitrate from drinking water with varying degrees of cost and system performance. In this study, the cost-effectiveness of the following nitrate removal options are compared for each of six small Nebraska towns: reverse osmosis, ion exchange (standard and nitrate selective resins), biological denitrification, and ion exchange with biological denitrification of the recycled brine. A multiple-criteria ranking procedure, fuzzy composite programming, was us'ed to determine which treatment method would remove the most nitrate for the least cost. The fuzzy methodology accounts for uncertainty in input data by allowing a range of values to be entered. The program then uses fuzzy distance measures to rank the different management options based on the output data. The technique is flexible because the preference of the decision maker can be incorporated into the analysis. Given the preferences that were highlighted in this research, the best treatment option for five out of six of these towns was ion exchange with a nitrate-selective resin and the worst treatment option for all six towns was reverse osmosis. Finally, a sensitivity analysis was done to determine how the results might change if selected preferences were modified.

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INTRODUCTION

In agriculturally intensive areas such as the Midwest, the major source of nitrate contamination has been linked to the excessive use of nitrogen fertilizers [1, 2]. The irrigated area in the United States has increased from nearly nineteen million acres in 1945 to more than forty-seven million acres in 1987 [3]. In Nebraska, about eight million acres are irrigated. Because nitrates are water soluble, excessive application and irrigation can cause much of the nitrate to leach into groundwater. Since we are now only beginning to see contamination resulting from agricultural chemical usage practices of thirty to forty years ago, the impact of the last fifteen years of intense agricultural chemical usage still remains to be seen [4].

Risk management involves managing situations in which risk exists that is deemed to be undesirable. This includes evaluating the risk/benefit relationship in establishing environmentally sound, cost-effective decisions. There are several strategies that risk managers can examine to reduce nitrate risk from drinking water supplies. These include controlling the sources of the contamination, developing alternate drinking water supplies, blending two or more water supplies, treating potable water at point of use, and treating the contaminated water before it is distributed. Controlling the sources of contamination include: reducing the residual nitrate at the end of the growing season when the potential is very high for off-season nitrate loss; the amount and timing of water and nitrogen applications need to be linked more closely with actual crop needs; the amount of nitrogen already in the soil, irrigation water, and manure should be accounted for; and excessive irrigation should be minimized [3]. Because it will take many years to see the results of improved water and fertilizer management, direct treatment may be the only immediate option for many communities.

The purpose of this study is to evaluate the cost-effectiveness of five treatment methods for nitrate reduction. The methods considered are: reverse osmosis; ion exchange with a standard resin; ion exchange with a nitrate-selective resin; biological denitrification; and ion exchange with a standard resin and biological denitrification of the spent regenerant brine. High-cost strategies usually provide high degrees of nitrate removal, while low-cost strategies may provide little or no effective nitrate removal. By utilizing a fuzzy-composite programming technique, a trade-off analysis can be performed that identifies the option that maximizes the treatment efficiency and minimizes the costs involved. This study illustrates how the fuzzy composite programming method can be used to address local water quality problems by applying it to six small towns in Nebraska with high nitrate levels in their drinking water.

NITRATES, HEALTH RISKS, AND TREATMENT OPTIONS

Nitrate itself is not toxic. Nitrate becomes a problem when it is converted into nitrite in the gastrointestinal tract. Because nitrate has one more oxygen atom than nitrite, nitrate can be changed into nitrite by microbes requiring oxygen. This can happen in the soil, in water, or in human bodies. Infants less than six months old are at greatest risk from high nitrate levels. When nitrate is consumed, a portion of it (about 10%) is converted to nitrite in the mouth and stomach.

After ingestion, the nitrite and any remaining nitrate are absorbed into the body through the intestine. Methemoglobinemia, or "blue baby syndrome" is a condition in which nitrite reacts with hemoglobin to form methemoglobin. Methemoglobin in the red blood cells does not carry oxygen. The oxygen-carrying capacity of the blood is, thus, lessened resulting in a blue skin color, asphyxia, and sometimes death. In addition to the slate-blue color, symptoms include diarrhea and vomiting.

Nitrite has also been determined to react in acid with amines and amides to form nitrosamines and nitrosamides, which were found to induce cancer in many organs of rodents. Specifically, nitrosamines induce tumors of the liver, kidney, esophagus, oral and nasal cavities, lung, trachea, urinary bladder, pancreas, and thyroid in rodents. Nitrosamides induce tumors of the glandular stomach, small intestine, brain, peripheral nervous system, bone and skin, acute myelocytic leukemia, and T and B cell lymphoma. The actual site of the induced tumors depends on the chemical, its route of administration, and the species of test animal. There is no other group of carcinogens that can produce such a wide variety of tumors [5]. Exposure to nitrosamines in food, cigarette smoke, industrial situations, or by formation in the stomach may cause human cancer. Nitrosamine formation is catalyzed by thiocyanate (secreted in saliva), iodide and bromide. It is therefore believed that nitrites may cause cancer of the stomach and esophagus in humans. Smokers have increased levels of saliva and, as a result, may be at greater risk for nitrosamine formation than nonsmokers.

As a result, new federal standards for nitrate and nitrite have taken effect in June 1992. These standards apply to all public water systems. The maximum contaminant level (MCL) for nitrite is 1 $mgNO_2$-N/L, and the MCL for nitrate is 10 $mgNO_3$-N/L [6, 7]. In 1989 the USEPA proposed that the ion exchange and reverse osmosis processes were the Best Available Technology (BAT) for nitrate and nitrite removal [8]. In addition to these BAT processes, three other processes for nitrate removal in drinking water are discussed in this study. These are: biological denitrification; ion exchange with biodenitrification of the recycled brine; and ion exchange with a nitrate-selective resin. The cost data used for these five nitrate removal processes can be found in the case study section of this article.

Reverse Osmosis

Osmosis is a natural process that occurs when two solutions of different concentrations are separated by a semipermeable membrane. Reverse osmosis (RO) is the pressure induced flow of water from higher to lower concentration through a semipermeable membrane. The applied pressure must exceed the osmotic pressure of the solution against the membrane. This forces pure water through the membrane while retaining virtually all of the ions.

Pretreatment of the feedwater often is required to protect the membrane and or to improve its performance. For RO systems, pretreatment usually consists of: adding chemicals such as sodium hexametaphosphate for carbonate and sulfate scale control; filtration; and lowering its pH by adding an acid. Typical post-treatment steps for municipal membrane processes include air stripping for stabilization, pH adjustment for corrosion control, and chemical addition for disinfection. A membrane design life of three to five years is common [9].

One of the largest drawbacks to the reverse osmosis treatment option is the disposal of the brine concentrate produced. The amount of brine varies, but for brackish water it usually falls in the range of 20 to 50 percent of the feedwater. Disposal methods include discharge to freshwater streams or lakes, the ocean, deep well injection, lined evaporation lagoons, irrigation, and dilution in domestic wastewater systems. The disposal method chosen is dependent on site conditions and federal, state, and local regulations in effect [10].

Biological Denitrification

In this process, microorganisms are introduced to the nitrate contaminated water and a carbon source is added as a food supply in an anoxic environment. What follows is a two-step reaction that reduces the nitrates to harmless nitrogen gas. Most denitrifying bacteria are heterotrophic and can use a wide range of carbon compounds (organic acids, sugars, and amino acids) as sources of electrons. The most often used carbon source are methanol and ethanol. The reaction equations are as follows [11]:

$$6NO_3^- + 2CH_3OH = 6NO_2^- + 2CO_2 + 4H_2O \tag{1}$$

$$6NO_2^- + 3CH_3OH = 3N_2 + 3CO_2 + 3H_2O + 6OH^- \tag{2}$$

Denitrification can occur naturally in the groundwater environment. Studies have shown that populations of denitrifiers do exist in both shallow and deep aquifer systems [11].

Above-ground biological denitrification can be carried out in either suspended or attached growth systems. In suspended growth systems the biomass is suspended in the reactor unit by means of constant mixing. An example of such a system is commonly referred to as a continuous upflow sludge blanket reactor (USBR) which contains a floc blanket of denitrifying bacteria with the flow of water moving from bottom to top.

In attached growth systems, a solid matrix is used in the reactor unit to support the bacterial biomass. Attached growth systems can contain either static media or expanding-bed media. Static media can include gravel or plastic support and can be operated with the flow of water moving in either a downflow or upflow direction. Expanding-bed media usually consists of sand which "expands" when it is fluidized as the flow of water moves from bottom to top. Because the bacterial growth appears as a thin film coating the support matrix, the expanding bed systems are said to have the highest denitrification rates per reactor volume and ease in removing excess biomass [12].

Although this process is not currently being used in the treatment of drinking water in the United States, it has proven to be very effective in the removal of nitrates in several pilot and full-scale demonstration plants in France and Germany [11]. Biological denitrification produces only a small amount of biological sludge to be disposed of. Because of its complexity it can be more expensive than other traditional treatments. Not only does the carbon source have to be added continuously in the appropriate stoichiometric amount, but post-treatment usually is required to remove microorganisms, excess carbon, and turbidity. Such post-treatment generally includes aerated sand or activated carbon filtration, ozonation, and/or chlorination [13].

Ion Exchange

The ion exchange process involves the exchanging of ions found in the water for other ions found on the ion-exchange resin. Ion-exchange material includes chemically prepared resins and clay minerals. The process of nitrate removal involves passing the contaminated water over a specially treated strong-base anion resin that will remove the nitrate ions from the water and replace them with chloride ions [11]: The column must be either completely or partially regenerated with 0.5-2.0 N (3 to 12%) sodium chloride (NaCl) before nitrate breakthrough. The brine must then be disposed of.

In the past, a high sulfate concentration in the raw water significantly reduced the nitrate removal efficiency of the resin. A raw water that is high in sulfate can result in short exhaustion runs with standard anion resins. This is because typical anion resins show a strong preference for sulfate ions over nitrate ions. Thus, sulfate ions are exchanged on the resin bed before nitrate ions.

A nitrate selective resin is one which prefers to exchange its chloride ions for nitrate over sulfate in normal drinking water concentrations. Advantages of using nitrate selective resins include: potential brine savings, improvement of treated water quality, and reduction in nitrate dumping [14].

The standard Type I and Type II resins have been approved by the Food and Drug Administration (FDA) for use in water treatment in the United States. The tributylamine and triethylamine (nitrate selective) resins are currently approved for use in European countries, but they are not currently approved by the U.S. FDA. They are, however, being used in several pilot water treatment plants [15].

Combined Ion Exchange and Biological Denitrification

Recent advancements have combined nitrate removal by ion exchange and regeneration of the resin by denitrification. Pilot studies have been conducted in the Netherlands and in the United States [14]. Although safe and economical, ion exchange is associated with the problem of brine disposal. When the spent ion exchange brine is regenerated in a biological denitrification reactor, the brine can be recycled. Thus, not only is the brine disposal problem minimized, but the salt needed to recharge the brine is reduced and the "dangerous" bio-mass of the biological denitrification process does not come in direct contact with the drinking water.

FUZZY COMPOSITE PROGRAMMING METHODOLOGY

Fuzzy set theory is an extension of basic interval analysis. Basic interval analysis is similar to probability statistics, but numeric "ranges" are analyzed instead of specific points. Fuzzy sets are used to define the level of uncertainty in both the costs and the benefits of the different nitrate treatment options. By using a composite program that can evaluate multiple indicator variables (such as capital costs, operation and maintenance costs, technical feasibility, and health risks), different nitrate risk management options can be compared. The composite program used for this analysis is a DOS-based program created by a graduate student [18]. The program used requires the decision maker to identify the ideal and worst values for all of the objectives (indicators). By calculating the graphical distance between the ideal state and the various alternatives, composite programming allows decision makers to choose the "best" option.

Selection of Indicators

The composite procedure involves combining various basic indicators for a given level to form a single indicator to be used at the next level [16]. To represent both the potential problems and benefits of each nitrate removal option, a set of basic indicators was chosen. These first-level indicators were then grouped into a smaller subset of second-level indicators. Finally the second level indicators were grouped into a subset of third level indicators from which the "best" option was chosen [17]. Figure 1 shows all three levels of indicators that were used to describe the important aspects of this study.

Ideal and Worst Indicator Values

Indicators can be quantity or quality based. Quantity based indicators are represented by actual numbers. Quality based indicators are those that are represented by an arbitrary scale and the decision maker's subjective option. Since actual data

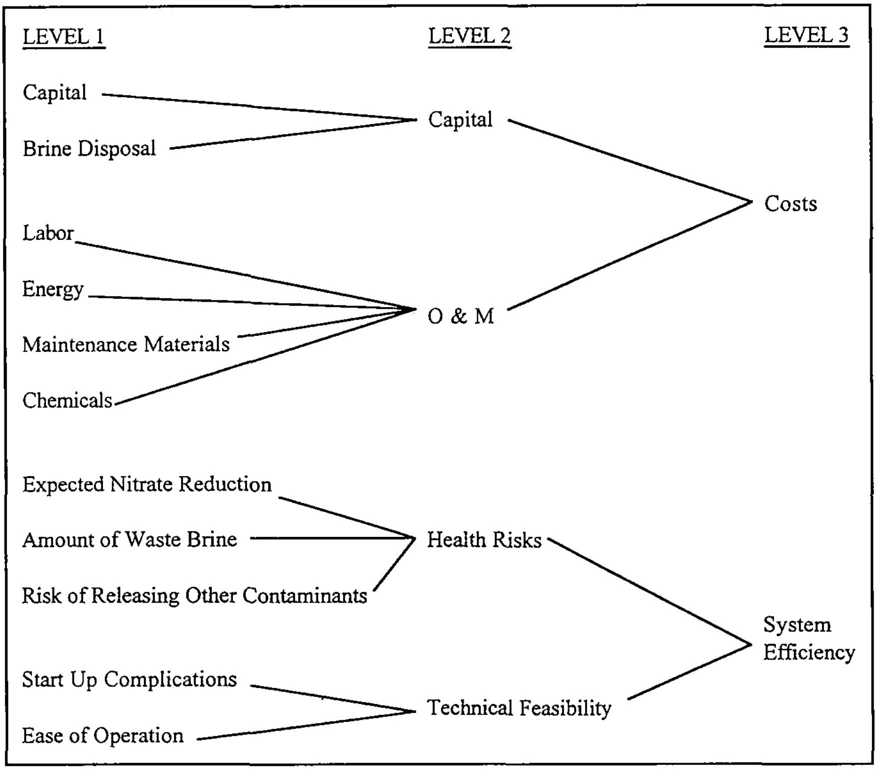

Figure 1. Composite structure of indicators.

were difficult to obtain for some of the basic indicators, quality based indicators were used. Listed in Table 1 are the quality based indicators used in this study and the possible ranges associated with them. A value of 0 represents: no nitrate reduction; no possibility of releasing contaminants into the product water; no start up complications; and a relatively easy operation of the treatment facility. An arbitrary value of 100 represents total nitrate reduction, and an arbitrary value of 5 represents a definite release of contaminants into the product water; the worst possible start up complications; or very difficult operation of the treatment facility, respectively. The remainder of the indicators were expressed quantitatively.

Fuzzy Trade-Off Analysis

Assigning values to the basic indicators to evaluate the various nitrate removal options contains elements of uncertainty. The methodology for consideration of

Table 1. Quality Based Indicators

Quality-Based Indicator	Minimum Possible Value	Maximum Possible Value
Expected nitrate reduction	0	100
Risk of releasing other contaminants	0	5
Start up complications	0	5
Ease of operation	0	5

uncertainty in this study was based on triangular fuzzy numbers with minimum, maximum, and typical values [18]. Basic indicator values may be interpreted as fuzzy members to characterize their uncertainty. The uncertainty of the value of each basic indicator can be represented by a most likely interval (i.e., the range at the membership level = 1.0) and a largest likely interval (i.e., the range at membership level = 0.0). These two intervals can then be used to construct the membership function for each basic indicator. If the most likely range is reduced to one point, the trapezoid becomes triangular-shaped, as shown in Figure 2 [16].

The units of the basic indicators vary and are, as a result, difficult to compare directly. Thus, the values of each basic indicator ($Z_{ih}(x)$) are transformed (normalized) into an index, $S_{ih}(x)$, by using the best and worst values, where "i" represents the "i^{th}" basic indicator, and "h" represents the degree of membership (h = 1.0 at the most likely interval, and h = 0.0 at the largest likely interval). The index is a value between 0 and 1 and is calculated as follows:

If $Bes(Z_i) > Wor(Z_i)$:

$$S_{ih}(x) = \begin{bmatrix} 1, & Z_{ih}(x) \geq Bes(Zi) \\ [Z_{ih}(x) - Wor(Z_i)]/[Bes(Z_i) - Wor(Z_i)], & Wor(Z_i) < Z_{ih}(x) < Bes(Z_i) \\ 0, & Z_{ih}(x) \leq Wor(Z_i) \end{bmatrix} \quad (3)$$

If $Bes(Zi) < Wor(Zi)$, then:

$$S_{ih}(x) = \begin{bmatrix} 1, & Z_{ih}(x) \leq Bes(Zi) \\ [Z_{ih}(x) - Wor(Z_i)]/[Bes(Z_i) - Wor(Z_i)], & Bes(Z_i) < Z_{ih}(x) < Wor(Z_i) \\ 0, & Z_{ih}(x) \geq Wor(Z_i) \end{bmatrix} \quad (4)$$

The methodology is incorporated into a microcomputer based program [18]. The best and worst values for the ith basic indicator can be assigned either manually or automatically by the program. The "automatic" option will use the overall best and worst values of the ith basic indicator from among the given strategies. The "manual" option allows the user to input the best and worst values. For this illustrative study the "automatic" option was always used, since this

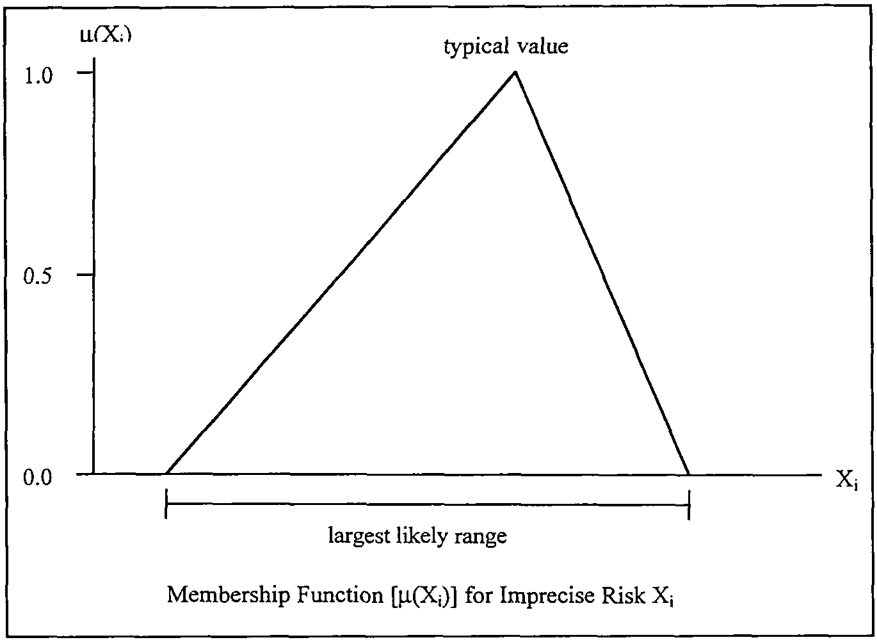

Figure 2. Triangular membership function (from [16]).

option reduces the most likely range to one point and the membership function simplifies by becoming triangular.

Determination of Weights and Balancing Factors

Weights and balancing factors are needed to compute the index values for the second and third level composite indicators. The weights are values between 0 and 1 reflecting the importance of an indicator relative to the other indicators of that level. The most important indicator should have the largest value assigned to its weight. The weights of the indicators for each level should sum up to one. Balancing factors are also assigned to each group of indicators. The balancing factors are greater than or equal to one and represent the importance of the maximal deviations of the indicators [18]. The balancing factors can be considered as a second weighting system reflecting the relative importance between groups of indicators. For example, a value of $p = 2$ for a given level minimizes the impact of the primary "indicator" weights and places more emphasis on the secondary "group" weights. A value of $p = 1$, on the other hand, maximizes the impact of the primary "indicator" weights. Since balancing factors are exponential, they can also force the larger indicators within a subgroup to be more strongly represented in the results, while minimizing the impact of the primary

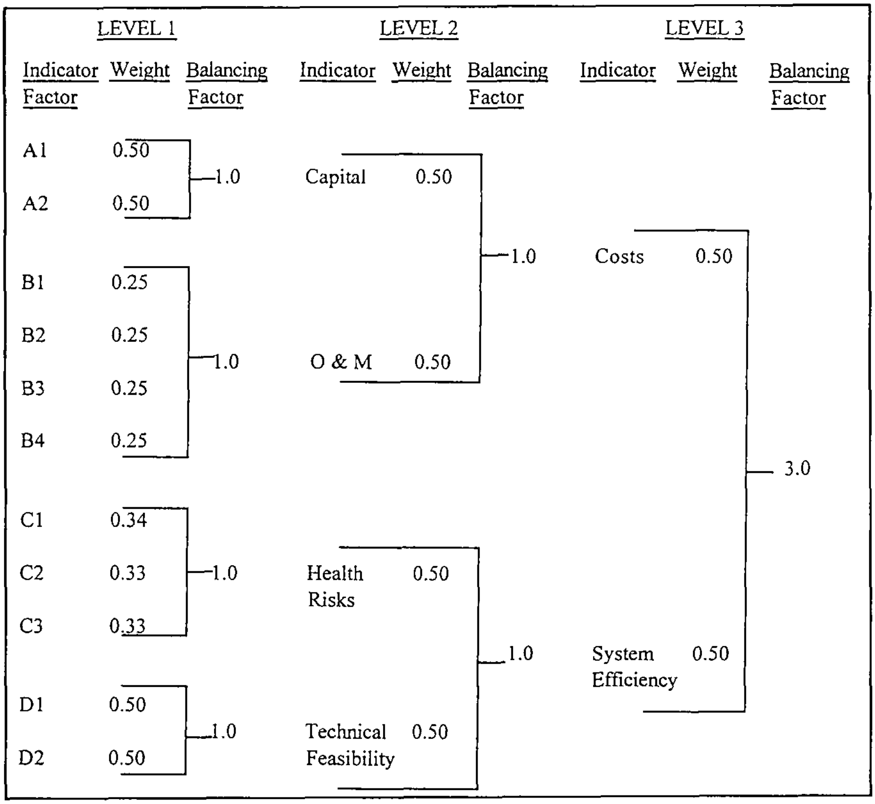

Figure 3. Initial weights and balancing factors.

weights. For this study the balancing factor assigned to level one and level two was 1 and the balancing factor assigned to level three was 3. The balancing factors for levels one and two have no effect, whereas the balancing factors for level three would cause the larger of cost and efficiency to contribute more to the result. The initial weights and balancing factors for this study are shown in Figure 3.

The index values for the second-level indicators are calculated as follows using the basic indicator index values ($S_{ihj}(x)$), the weights (w_i) and the balancing factors (p_j).

$$L_{jh}(x) = \left[\sum_{i=1}^{nj} w_{ij} \left(S_{ihj}(x) \right)^{p_j} \right]^{p_j^{-1}} \tag{5}$$

where: nj = the number of elements in second-level group j
S_{ihj} = the index value of the ith basic indicator in second-level group j
w_{ij} = the weight reflecting the importance of basic indicator i in second-level group j
p_j = the balancing factor for group j

Using the second-level index values, the third-level index values are calculated as follows:

$$L_{kh}(x) = \left[\sum_{i=1}^{nk} w_{jk} \left(L_{jhk}(X) \right)^{p_k} \right]^{p_k^{-1}} \tag{6}$$

where: nk = the number of elements in the third-level group k
L_{jhk} = the index value of the second-level group j in the third-level group k
w_{jk} = the weight reflecting the importance of each second-level group j
p_k = the balancing factor for group k

The final step in the composite programming analysis is to compare the index values of the third-level indicators. In this study there were two third-level indicators: cost and system performance. The final composite index value $L_h(x)$ is calculated as follows:

$$L_h(x) = \left[\sum_{i=1}^{2} w_k \left(L_{kh}(X) \right)^{p} \right]^{p^{-1}} \tag{7}$$

where: L_{kh} = the index value of the third-level group k
w_k = the weight reflecting the importance of each third-level group k
p = the balancing factor for the final trade-off

Ranking the Risk Management Options

The nitrate treatment options can then be ranked based on the fuzzy numbers assigned to each of them. Let L(x) be the fuzzy number representing the final composite indicator for nitrate treatment option x. The uncertainty of the L(x) value can be represented by a triangular-shaped membership function, μ[L(x)]. The membership function, μ[L(x)], can then be calculated as follows [18]:

$$\mu[L(x)] = \begin{bmatrix} 1, & r_{\min} \le L(x) \le r_{\max} \\ (L(x) - R_{\min})/(r_{\min} - R_{\min}), & R_{\min} \le L(x) < r_{\min} \\ (L(x) - R_{\max})/(r_{\max} - R_{\max}), & r_{\max} \le L(x) < R_{\max} \\ 0, & elsewhere \end{bmatrix} \tag{8}$$

Where r_{min} and r_{max} equal the most likely values, and R_{min} and R_{max} equal the maximum possible values of the third-level composite indicator. In this study

$r_{min} = r_{max}$ since the most likely minimum and maximum values are represented by the same value.

Five different nitrate risk-management options were examined in this study. The closer $\mu[L(x)]$ is to "1", the better the risk management option. There are five fuzzy numbers [L(1) . . . L(5)] that now must be ranked relative to each other. Composite programming ranks these five options by using a maximizing set and a minimizing set [18]. The membership functions of the maximizing set, $\mu_M(L)$, and the minimizing set, $\mu_G(L)$ are given as follows:

$$\mu_M(L) = \begin{bmatrix} (L - L_{\min} / (L_{\max} - L_{\min}), & L_{\min} \le L \le L_{\max} \\ 0, & elsewhere \end{bmatrix} \tag{9}$$

$$\mu_G(L) = \begin{bmatrix} (L - L_{\max} / (L_{\max} - L_{\min}), & L_{\min} \le L \le L_{\max} \\ 0, & elsewhere \end{bmatrix} \tag{10}$$

Then the left and right utility values, $U_L(x)$ and $U_R(x)$, can be calculated as follows:

$$U_L(X) = \max(\min(\mu_G(L), \mu[L(X)]) \tag{11}$$

$$U_R(X) = \max(\min(\mu_M(L), \mu[L(X)]) \tag{12}$$

From these left and right utility values an overall ordering value is then assigned to each nitrate risk management option. The total utility or ordering value for strategy "x" is: $U(x) = [U_R(x) + 1 - U_L(x)]/2$. This ordering value is closest to the ideal point when one utility value is maximized and the other utility value is minimized. Thus, the option that has the highest numerical ordering value is selected as the best option. Graphically, the best option is the fuzzy number, represented by a box at different membership levels, that is closest to the ideal point.

CASE STUDY

A case study illustrating the methodology is presented.

Selecting the Case Study Towns

Six Nebraska towns were chosen for analysis in this research project. All six of these towns were chosen because they had nitrate levels greater than the mandated, MCL of 10 $mgNO_3$-N/L. Data was gathered on these towns from records at the Nebraska Department of Health. None of these towns had sulfate or total dissolved solid levels of any significance. Thus, it was assumed that any chemical variability in the water samples was too small to significantly affect any of the treatment options. Significant levels of sulfate and/or total dissolved solids may be expected to reduce the efficiencies of ion exchange and reverse osmosis, respectively. If either of these variabilities would have been present, some of the qualitative and quantitative level 1 indicators would have had to have been modified (i.e., nitrate reduction decreased and O & M increased). Some pertinent data concerning these towns are summarized in Table 2.

Cost Data Analysis

Cost data were obtained through literature and then updated to 1994 levels using the Engineering News Records (ENR) Construction Cost Index, Skilled Labor Index, and Materials Index. Chemical prices were obtained from several local chemical supply companies and energy prices were obtained from the local electric utility [19]. Construction, operation and maintenance costs for ion exchange were calculated from [20]. The costs are based on pressure ion exchange units with nitrate concentrations up to 50 mg/L (as N) and sulfate concentrations up to 100 mg/L.

Capital, labor, energy and chemical costs for the ion exchange plant with the nitrate selective resin were assumed to be the same as for the standard resin. Because the expected nitrate reduction for the nitrate selective resin was assumed to be 5 percent greater than for the standard resin, brine disposal costs and the amount of waste brine were also assumed to be 5 percent greater. The qualitative indicator values to start up complications and ease of operation were assumed to be the same as for the standard resin. The risk of releasing other contaminants was reduced, however, since "dumping" or peaking is significantly reduced with the nitrate selective resins.

Construction, operation and maintenance costs for reverse osmosis were calculated from [20]. The construction cost data were developed for a single stage treatment system capable of treating a TDS concentration up to 2,000 mg/L for low pressure membranes and 10,000 mg/L for high pressure membranes. A recovery rate of 75 percent was assumed for all RO plants. The cost of brine disposal was calculated based on the amount of waste brine using the same procedure used for the ion exchange process.

Table 2. Information Related to Case Study Towns

Town	Population	Water Use gal/d (m^3/d)	Nitrate Level $mgNO_3$-N/L	Recent Situation[a]
Adams	480	135,000 (511)	13.8	New IE Plant with bypass
Waterbury	95	8,500 (32)	14.3	Well head protection
Milford	1,886	940,000 (3558)	12.1	Recent drop in nitrate levels
Creighton	1,222	1,100,000 (4164)	12.0	New RO Plant with bypass
Page	191	26,000 (98)	10.1	New IE Plant with bypass
Wood River	1,156	190,000 (719)	15.2	New Water Source (1991)

[a] RO = reverse osmosis, IE = ion exchange.

Construction, operation and maintenance costs for biological denitrification were also calculated from [20]. Since biological denitrification is not currently being used in the United States for treating drinking water, several assumptions had to be made in order to estimate the cost data. These estimates may not be very accurate and their use is intended to illustrate the application of the ranking methodology to a variety of nitrate treatment options.

Ion exchange with biological denitrification of the recycled brine option is, as mentioned earlier, a new concept. Since limited cost data are available, some preliminary assumptions were used. Similar to the biological denitrification process, there would be no waste brine or brine disposal costs. The capital and operation and maintenance costs were estimated by using 100 percent of the ion exchange (standard resin) costs plus 50 percent of the biological denitrification costs. Because recent data indicated that there is a potential suit savings of 47 percent [21], 53 percent of the chemical costs for ion exchange plus the chemical costs for biological denitrification were used for the ion exchange with biological denitrification chemical cost data.

It is realized that many of the assumptions involving the biological denitrification are preliminary and uncertain. It is for the purpose of illustration that these five treatment options are being compared in this study. It must be kept in mind that any results using the fuzzy ranking technique may change once actual cost data become available for all of these treatment options. Process efficiencies were assumed to be at the following levels:

Ion Exchange (standard resin) = 80 percent
Ion Exchange (nitrate selective resin) = 85 percent
Ion Exchange w/bio denitrification of the brine = 90 percent
Biological Denitrification = 95 percent
Reverse Osmosis = 75 percent

These efficiencies are subjective and, as a result, they are appropriately handled by fuzzy set approaches.

For the ideal and worst values of ion exchange (standard resin), ion exchange (nitrate selective resin), and reverse osmosis, the most likely values for: capital, brine disposal, labor, energy, maintenance materials, chemicals, and amount of waste brine were used. A 10 percent allowance of variability (+ or –) was built in which represents the uncertainty involved. These same indicators for biological denitrification and ion exchange with biological denitrification of the brine used the most likely values plus or minus 30 percent. These larger "fuzzy" ranges were used because the biological treatment process is relatively new and cost data are generally unavailable. The ideal and worst values for the expected nitrate reduction, risk of releasing other contaminants, start up complications, and ease of operation were based on literature review and, as mentioned earlier, are qualitative values. The ideal and worst points for all six towns are shown in Table 3.

Table 3. Ideal and Worst Points for All Six Towns

Indicators	Ideal Points	Worst Points
Capital	–1.00	1.00
Brine disposal	–1.00	1.00
Labor	–1.00	1.00
Energy	–1.00	1.00
Maintenance materials	–1.00	1.00
Chemicals	–1.00	1.00
Expected nitrate reduction	+1.00	–1.00
Amount of waste brine	–1.00	1.00
Risk of release	–1.00	1.00
Startup complications	–1.00	1.00
Ease of operation	1.00	–1.00

Costs data were estimated for plants of the following capacities and then interpolated as needed for the six case studies: 2,500; 10,000; 50,000; 100,000; 500,000; and 1,000,000 (gal/day). The results are shown graphically for ion exchange (Figure 4), reverse osmosis (Figure 5), and biological denitrification (Figure 6). These graphs show that there is an apparent linear relationship between costs and plant size. A linear relationship between costs and plant size was also found in a previous study involving ion exchange and biological denitrification [22].

RESULTS

The results of using the fuzzy ranking techniques for the five nitrate removal options for Adams, Creighton, Milford, Page, Waterbury, and Wood River are shown in Figures 7-12. The results of this illustrative case study indicate that based upon the assumptions made, ion exchange appears to be the most cost-effective treatment option for removing nitrates from small town water supplies. The nitrate selective resin was deemed to be the hypothetical best choice by the fuzzy composite program for Adams, Creighton, Milford, Page, and Wood River. The standard resin was the best choice for Waterbury. Biological denitrification and ion exchange combined with biological denitrification of the spent brine came in third and fourth, respectively, for all six of the case studies. The actual values for options one through four are very close and modifying any of the input data might shift their ranking. For this illustrative case study, reverse osmosis was found to be the least attractive of the five treatment options due to the large expense involved in building lined evaporation lagoons for the disposal of the waste brine.

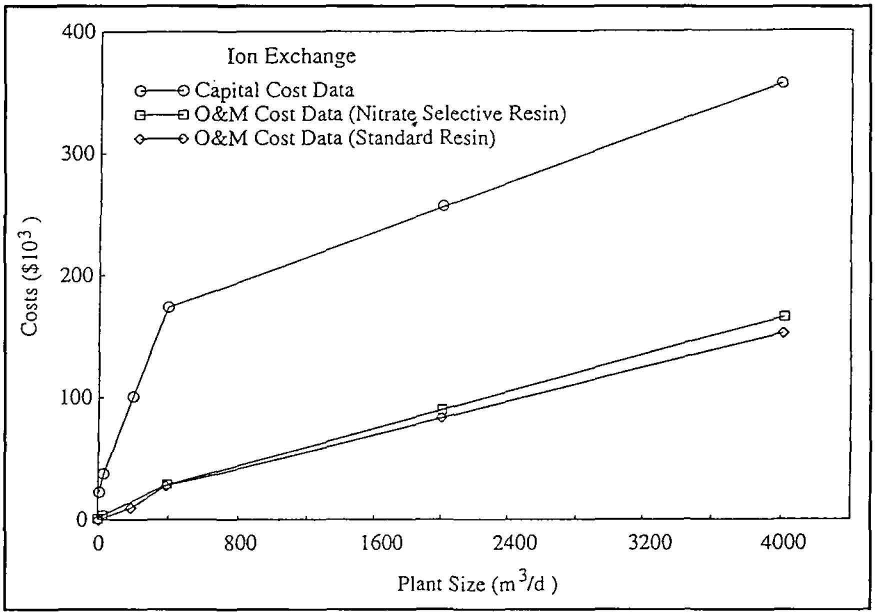

Figure 4. Unit cost data for ion exchange.

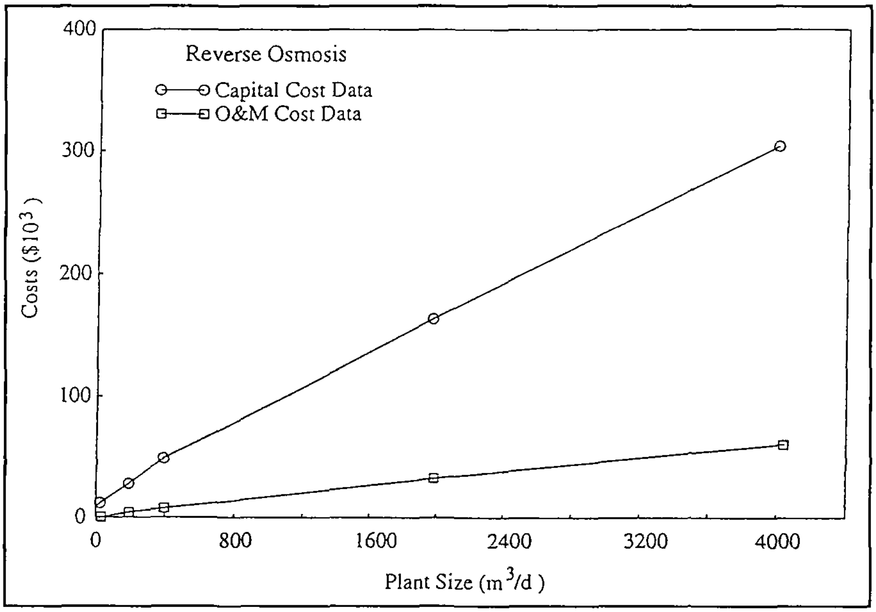

Figure 5. Unit cost data for reverse osmosis.

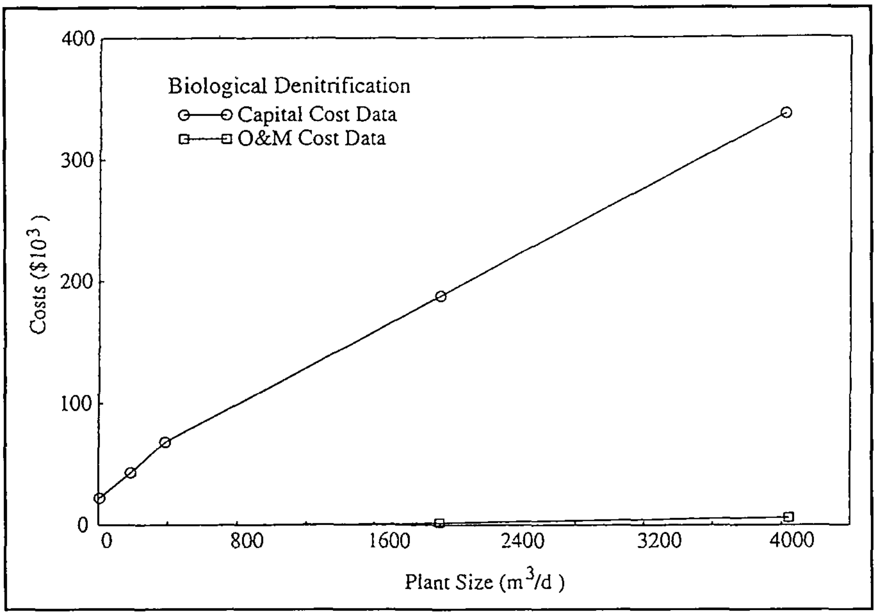

Figure 6. Unit cost data for biological denitrification.

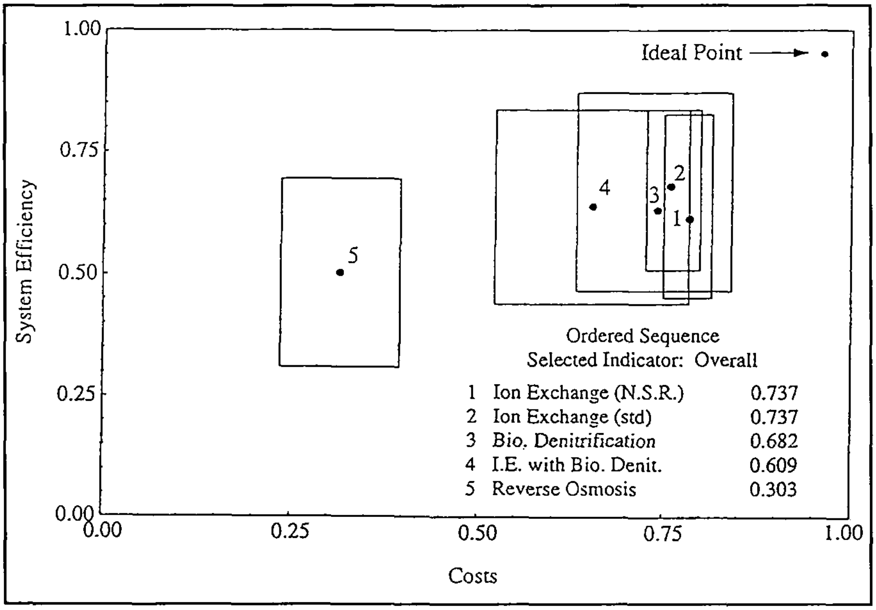

Figure 7. Results of fuzzy composite analysis for Adams, NE.

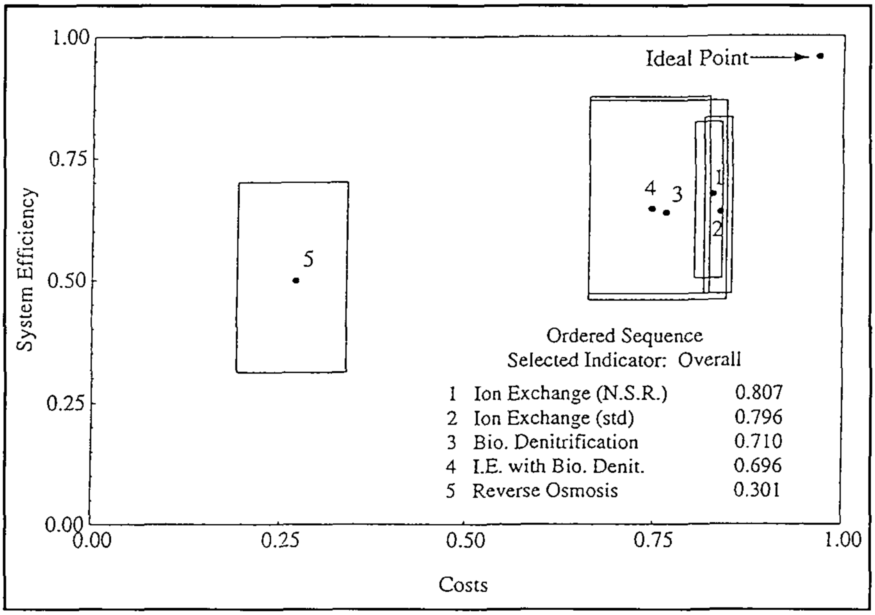

Figure 8. Results of fuzzy composite analysis for Creighton, NE.

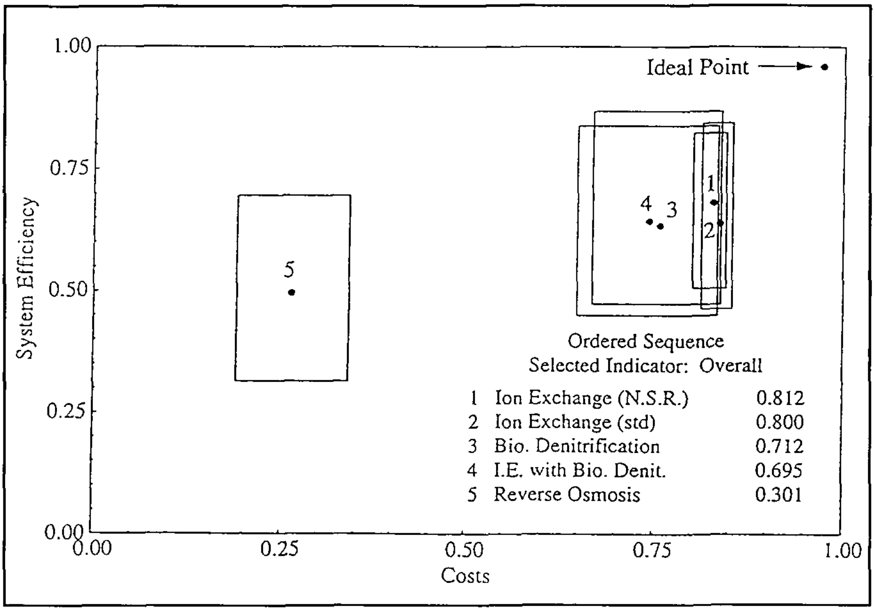

Figure 9. Results of fuzzy composite analysis for Milford, NE.

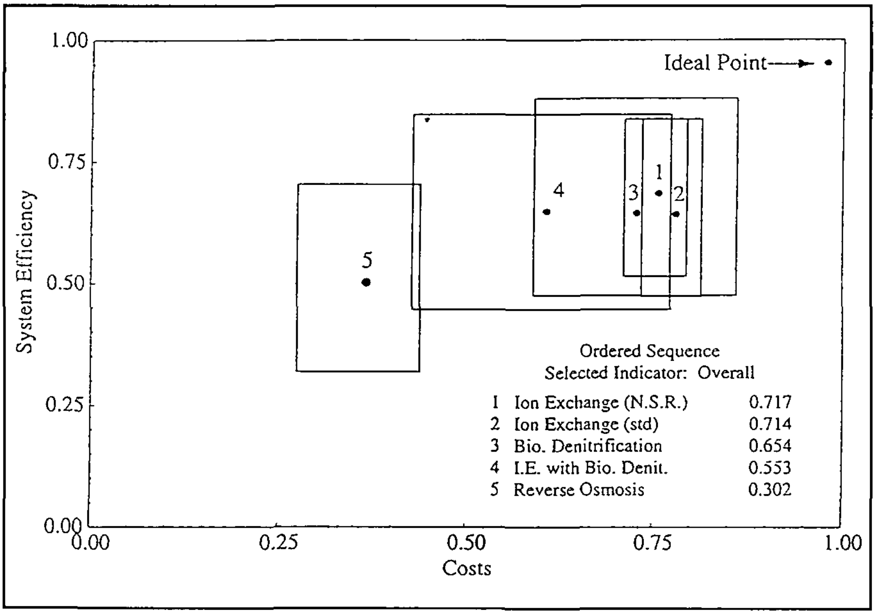

Figure 10. Results of fuzzy composite analysis for Page, NE.

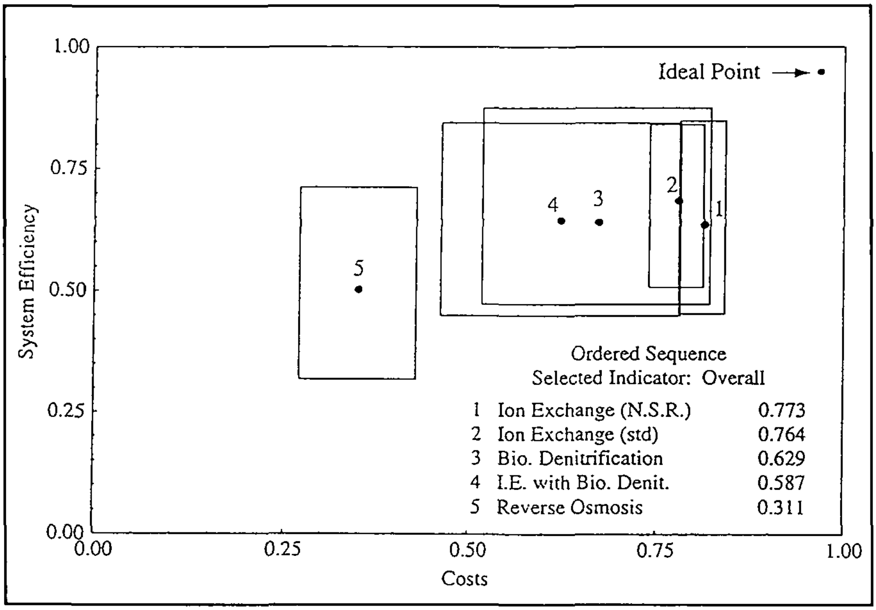

Figure 11. Results of fuzzy composite analysis for Waterbury, NE.

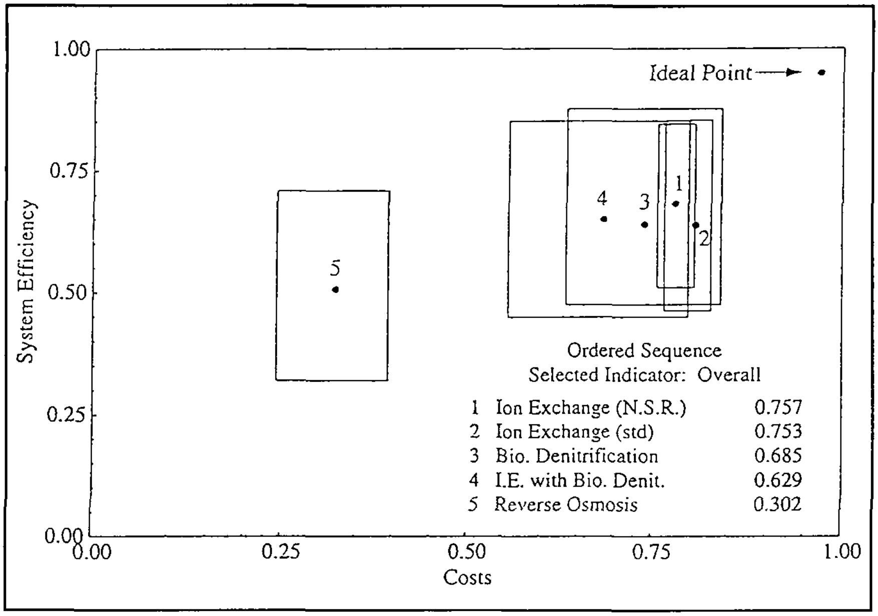

Figure 12. Results of fuzzy composite analysis for Wood River, NE.

The dots on each of the graphical results represent the most likely input data while the squares around each dot represent the fuzziness (the minimum and maximum input data). The dots can be said to represent the results of a "crisp" analysis using the most likely input data.

Sensitivity Analysis

A sensitivity analysis was completed in order to determine how the weight and balancing factor selection impacted the results. For example, weighing costs more heavily than system efficiency in the third level might produce different results than those obtained by weighing them equally. In order to obtain a better understanding of how a change in either the weights or the balancing factors might affect the final rankings of the five treatment options, a sensitivity analysis was done for Adams, NE on the weights (with the initial balancing factors held constant) and then on the balancing factors (with the initial weights held constant). The final results of these sensitivity tests are shown in Tables 4 and 5.

Each of the nine different weighting schemes resulted in most or all of the treatment options changing rank. Reverse osmosis remained in last place for all but one weighting scheme. The balancing factor schemes resulted in no rank change of the treatment options. Thus, the above results indicate that the weights

Table 4. Relative Ranking (1 = Best, 5 = Worst) of the Sensitivity Analysis Weighting Scheme for Adams, NE[a]

Treatment	w1	w2	w3	w4	w5	w6	w7	w8	w9
IE (standard resin)	1	1	3	2	3	2	4	1	4
IE (nitrate selective)	2 (tied)	2	4	1	4	1	3	2	3
IE w/Biodenitrification	4	3	1	3	2	3	2	4	2
Biodenitrification	3	4	2	5	1	4	1	3	1
Reverse Osmosis	5	5	5	4	5	5	5	5	5

[a] IE = ion exchange, w1 = initial weighting scheme, w2 = weighting scheme #2, etc.

Table 5. Relative Ranking (1 = Best, 5 = Worst) of the Sensitivity Analysis Balancing Scheme for Adams, NE[a]

Treatment	p1	p2	p3	p4	p5	p6	p7	p8
IE (standard resin)	1	2	2	2	2	2	2	2
IE (nitrate selective)	2 (tied)	1	1	1	1	1	1	1
IE w/Biodenitrification	4	4	4	4	4	4	4	4
Biodenitrification	3	3	3	3	3	3	3	3
Reverse Osmosis	5	5	5	5	5	5	5	5

[a] IE = ion exchange, p1 = initial balancing scheme, p2 = balancing scheme #2, etc.

are much more sensitive than the balancing factors. As the weighting schemes were changed, the ranking of the treatment options changed considerably. As the balancing schemes were changed, the ranking of the treatment options remained the same.

Because each treatment option varies considerably in its ranking between weighting schemes, there appears to be no one robust option for all situations. Depending on the circumstances for each real-world situation, the weighting schemes will vary. The only certainty appears to be that reverse osmosis is the worst choice of the five treatment options. When brine disposal is weighted more heavily than capital expense, biological denitrification and ion exchange with biological denitrification of the brine fall into first and second place, while the ion exchange options fall into third and fourth place. When capital is weighted more heavily than brine disposal these options were switched, with the ion exchange options falling into first and second place and the biological options falling into third and fourth place. Thus, if a community under consideration has a lot of land for brine disposal and lacks financial resources, ion exchange will probably rank at the top.

CONCLUSIONS

This illustrative study demonstrates how the fuzzy composite programming technique can be used for determining the preferred water treatment option given many "uncertain" parameters. This fuzzy ranking technique can be used by water supply managers that need to make a risk management decision involving multiple options and multiple measures of performance.

This study also demonstrates how the fuzzy composite program accounts for uncertainty in the cost or efficiency data by using value "ranges." The uncertainty is incorporated directly into the decision making process.

Six studies were used to illustrate the methodology. The following conclusions can be made based on the results:

- Ion exchange appeared to be the most cost-effective method for removing nitrates from small town water supplies. The nitrate selective resin was deemed the best choice by the fuzzy set analysis for Adams, Creighton, Milford, Page, and Wood River. The standard resin was the best choice for Waterbury. The values between the nitrate selective and the standard resin ion exchange treatment options were very close and should be considered to be "tied" for first place.
- Biological denitrification and ion exchange with biological denitrification of the spent brine came in third and fourth, respectively, for all six of the case studies. Again, the values for both of these options are very close. Because of the lack of comparable cost data for these two methods, their costs were estimated conservatively and could easily change when actual data become available. Either of these two options might possibly be the best treatment method in the near future. Ion exchange with biological denitrification of the spent brine especially appeared to be promising for removing nitrates efficiently.
- Reverse osmosis appeared to be the least attractive of the five treatment options. This was probably due to the large waste brine disposal costs and the lower nitrate removal efficiency. Evaporation lagoons would have to be built for the 25 percent reject water.

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