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Cost-Effectiveness Analysis of Waste Management Systems

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ABSTRACT

Cost effectiveness techniques have been used to identify the most cost effective commercially available waste-water treatment and disposal system for 500- and 1000-man military camps. Unit costs (cents per thousand gallons treated—capital plus operating) were developed using manufacturers' data. System effectiveness was determined using a decision weighting model based on paired comparisons. Results of this study have provided the Navy with guidance in terms of waste management systems that should be selected for use at advanced bases. Furthermore, this study is one example of how systems technology can be used in the solution of complex environmental quality management problems.

Introduction

A wide variety of commercially developed processes are generally available for treatment of waste water from small communities, industries, restaurants, motels, camp sites, etc. In addition, significant variations exist in both cost and performance characteristics from one manufacturer to another within the same process. Consequently, the selection of economic and effective systems from among the alternatives available is not a casual

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exercise. An investigation was conducted to determine the most cost-effective system for the disposal of sewage at advanced military bases. The specific objective was to identify highly cost-effective commercially available systems, equipment, and related hardware which can be selected for 500- and 1000-man military camps.

Background

Remote locations (where most of the military bases are built) impose severe logistic constraints not only on the initial system delivery and installation, but also on system maintenance due to the difficulty of supplying spare parts and repair tools. Thus, advanced base sanitary facilities must be simple to build and simple to operate. Only construction skills and equipment within or available to military forces can be relied upon for construction. Similarly, operation and maintenance of the completed facilities must be within the capabilities of petty officers who may possess little prior applicable training or experience. For maximum effectiveness, construction time should be as short as possible to reduce planning time and to permit quick response to changes in operational requirements which occur rather frequently. Finally, minimal capital and operating costs are desirable in the general interest of economy. Difficulties in providing low cost facilities are compounded by the fact that advanced bases are, by their nature, temporary facilities with expected lives, and hence amortization periods, of five years or less.

During recent years, waste treatment facilities specially designed for relatively small flows from small communities, camps, motels, etc., have become commercially available. These plants, commonly referred to as "packaged waste treatment plants," have many features (simplicity, compactness, reliability, and operational flexibility) that render them potentially suitable for use at advanced military bases. The work reported in this paper was directed toward a cost-effectiveness analysis of those systems that are presently commercially available; the specific objective was to identify the most cost effective systems for use at advanced military bases in remote areas. A comprehensive survey of treatment plant and hardware manufacturers was conducted to obtain data on available systems. Technical and economic data supplied by various system manufacturers were used to perform the cost-effectiveness analysis of these systems.

Cost-Effectiveness Methodology

APPROACH

Cost-effectiveness analyses involve two types of evaluation. The first and most straightforward is cost analysis. This involves the delineation of all major system components and the development of capital and operating cost estimates for each. A second, and often the most difficult (in complex systems), is the effectiveness evaluation whereby one attempts to generate a single cardinal measure or indicator of effectiveness based upon multiple considerations. The essence of cost-effectiveness analysis *per se* then involves the trade-off of cost with effectiveness to identify the most cost-effective alternative(s).

Economic analyses of engineering systems were traditionally based strictly on cost considerations. Initially, engineers were concerned with least-cost solutions that met fixed requirements or constraints; economic efficiency was measured by cost minimization without recourse to benefits. Next, evaluations centered about net cost or net savings which represented the difference between total cost incurred and any resultant savings or benefits which could be expressed in monetary units. It has been recognized however, that combining costs and benefits into a single measure will not necessarily indicate the most economically efficient alternative. Consequently, keen interest developed in the use of cost-benefit analyses which focused attention on the cost/benefit ratio as the measure of economic efficiency.

Benefit-cost analyses are satisfactory only so long as all benefits can be expressed in dollars. This is not the case, however, in evaluating wastewater treatment and disposal systems for use at advanced military bases, since the overall effectiveness of any given alternate system depends on multiple criteria or measures of effectiveness (reliability, size, ease of operation, etc.) which cannot be expressed directly in monetary units.

Thus selection of one system from among a group of alternatives, when multiple criteria are to be considered, poses a complex problem in decision making. The difficulty arises from the multiplicity of considerations which somehow must be weighed against one another in order to reach a decision. This usually indicates a need for some type of decision-weighting model. Decision-weighting models have been criticized by several authors, and when taken in context, many criticisms are valid. One cannot escape the fact, however, that somehow the decision maker must make a final choice. Somehow he must weigh all the diverse factors so as to reach a final overriding value assessment and to arrive at a choice. A methodology is outlined below for doing this in an explicit manner.

Historically, decision makers have dealt with multiple-criteria problems largely on the basis of subjective judgment and intuition. Personal judgments have been used both to effect trade-offs among the relative importance of various effectiveness criteria and to assess the effectiveness of different levels of predicted performance. Problems of physical interaction among performance consequences and interdependencies among effectiveness criteria have similarly been handled on an intuitive basis.

If the decision problem under consideration is very simple, and if the consequences of making a poor decision are relatively inconsequential, the subjective, intuitive approach may be the best way to proceed. Additional gains that might be realized from formalizing and systematizing the decision process probably would not justify the extra time, cost, and effort required. However, when the decision problem becomes complex and the consequences become important, strict reliance on subjective judgment is not satisfactory. In these cases, a need exists for a systematic procedure to develop an explicit, logically consistent, and replicable procedure to aid in the assessment of effectiveness.

It should be emphasized that explicitness, logical consistency, and replicability do not preclude the use of judgment. One can, however, attempt to make his judgments in an objective manner rather than in a subjective one. Judgments must be used both in trading off relative importance among effectiveness criteria and in assessing measures of effectiveness for various performance levels. When judgment is used, it should be made explicit, should be thoroughly scrutinized for logical consistency, and should be elicited by a uniformly applicable procedure.

The advantages of such a procedure are several. The explicit statement of assumptions will help ensure that personal judgments are not based on false information. In addition, a decision process thoroughly scrutinized for logical consistency will help to remove random elements and inconsistencies from the decision process.

The decision-weighting model employed in the effectiveness analysis of advanced-base wastewater treatment and disposal systems may be outlined with the aid of Figure 1. Assume that one is faced with a series of alternative concepts (A_1, A_2, A_3, . . .,A_m) which must be evaluated in terms of several measures of effectiveness (M_1, M_2, M_3, . . .,M_n). The general procedure is to first assign relative weights (w) to each of the n measures of effectiveness. These weights merely reflect the relative importance of each of the measures of effectiveness. A convenient ground rule to follow in deriving these relative weights is that they should add up to one; when this is done the resulting overall effectiveness ratings (computed as the sum of weighted individual effectiveness ratings) may be subjected to the same interpretation as the effectiveness ratings or scores (discussed below) assigned to individual performance levels. This renders far more manageable the task of checking assigned weights for intuitive reasonableness and consensual validation.

A score or rating is then assigned which reflects the degree to which each alternative satisfies one of the effectiveness measures. Referring to Figure 1, r_{ij} is the rating of alternative A_i with respect to effectiveness M_j. The overall effectiveness of any given alternative is then equal to the sum

	Measures of Effectiveness (M) and Relative Weights (w)					
Alternate System Concepts	M_1 (w_1)	M_2 (w_2)	. . .	M_j (w_j)	. . .	M_n (w_n)
A_1				.		
A_2				.		
.				.		
.				.		
.				.		
A_i	. . . .	. . . .	. . . .	r_{ij}		
.						
.						
.						
A_m						

Effectiveness of alternative i $\equiv E\,[A_i] = \sum_{j=1} w_j r_{ij}$

where

$$\sum_{j=1}^{n} w_j = 1$$

$r_{ij} \equiv$ Rating of alternative i with respect to measure j

Figure 1. Methodology for System-Effectiveness Analysis

of the product of each rating multiplied by its relative weight; the calculation procedures are outlined in Figure 1.

To implement the above decision procedure, judgments are required at two critical steps: first, in the assignment of weights; second, in the assignment of ratings. The need for judgment on these elements cannot be avoided since they must, by definition, reflect the decision-maker's opinion (as opposed to an absolute measure) on the relative importance of the measures and on the relative merit of alternatives being considered. One can, however, use a procedure to render these judgments objective, explicit, consistent, and replicable. Such a procedure, based on the technique of paired comparisons, is outlined below.

Technique of Paired Comparisons

The decision model employed in the effectiveness analysis is based on a technique that forces the decision maker to make a series of paired comparisons. In considering each pair of items a decision (judgment) is made as to which item is more important or scores higher. As will be shown in the following discussion and example, the decision maker then relates all decisions to a common reference and makes the thought processes followed in assigning his judgments explicit.

The paired comparison technique also has the advantage that the decisions required of the decision maker are simple. He need compare only two items at a time, as contrasted to the dozens of items that would need to be considered simultaneously (at least implicitly) if one attempted a direct assignment of weights and ratings. Decision weighting models and the paired comparison technique are discussed extensively by Eckenrode[1] and Miller.[2] The procedure following is a condensation of the basic technique outlined by Miller. Other less sophisticated applications of the paired comparison technique have also been proposed but their simplicity negates their utility.[3,4]

The technique is best illustrated by an example. Throughout this discussion, the reader may find it helpful to refer to Figure 1: Consider that three alternative systems, A_1, A_2, and A_3 are to be evaluated; It is further determined that only three criteria or measures of effectiveness are relevant to the evaluation. For illustration purposes, let these be M_1–reliability; M_2–weight; and M_3–size. In selecting measures of effectiveness one must ensure that they are:

1. *complete* (i.e., all criteria which the decision maker is able and willing to formulate and consider must be included)
2. *mutually exclusive* (i.e., individual criteria must neither encompass nor be encompassed by other criteria on the list)
3. *free of effectiveness interdependence* (the effectiveness of a given alternative with respect to any one measure should be independent of its effectiveness with respect to any other measure)

Returning to the example, it has been determined that only three measures of effectiveness–reliability, weight, and size are to be considered. The next step is to determine the relative weights to be assigned to each measure of effectiveness the relative importance the decision maker wishes each to have in determining his decision. The effectiveness measures are then tabulated in a list. It is often convenient to structure this list by ranking the items in order of decreasing importance. Starting at the bottom of the list, successive paired comparisons are made between contiguous measures; for each comparison the decision maker indicates, in terms of a ratio, the perceived relative importance of the two items being considered. Stated alternatively, the decision maker indicates the rate at which he would be willing to accept reduced satisfaction with one criterion in return or increased satisfaction with another.

		Relative Importance		*Normalized*
Effectiveness measures		*With respect to next item on list*	*With respect to last item on list*	*relative weights*
M_1	Reliability	3	6	0.67
M_2	Weight	2	2	0.22
M_3	Size	—	1	0.11
			$\Sigma=9$	$\Sigma=1.00$

Figure 2. Assignment of Weight to Measures of Effectiveness

For illustration purposes, assume that weight is twice as important as size, and reliability is three times as important as weight. The relative importance of each item, with respect to the one immediately bedow it on the list, is then indicated (see Figure 2). One then calculates by simple multiplication the importance of each item relative to the last one on the list. In the example being considered, weight is twice as important as size, and reliability is six times (2 X 3) as important as size. These values are indicated in the third column of Figure 2; in some cases, this column can be set down directly. The best approach depends in part on the type of information one has to work with and also on the psychological preferences of the decision maker. By normalizing this third column (so that the sum of the individual values is 1), one can derive the relative weights (w) for each of the measures of effectiveness; these values are set down in column 4*. Although this procedure guarantees that the resultant weights will possess certain desirable logical properties, it must be emphasized that their validity depends upon the decision maker's ability to provide accurate judgments in making the paired comparisons.

Having derived the relative weights in a consistent and explicit manner, one then uses a similar procedure to derive the respective rating scores (r_{ij}). Consider first the assignment of ratings to the three alternative systems with respect to effectiveness measure M_1, reliability. The reader is referred to Figure 3 for the following discussion. The alternatives may be tabulated in any order. Successive paired comparisons are then made between contiguous alternatives on the list, starting at the bottom and working up. For each comparison the decision maker makes a judgment about the relative degree to which each of the alternatives satisfies the effectiveness measure under consideration. As in the case of assigning weights to the effectiveness measures, the decision maker is asked to indicate, in terms of

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* The third column of numbers contains all the information needed to establish relative weights, but for reasons mentioned earlier, it is desirable to have the weights sum to 1; this is the only reason for computing the averaged weights listed in the fourth column of Figure 2.

Effectiveness measures	*Alternative systems*	*With respect to next alternative*	*With respect to last alternative*	*Ratings, r_{ij}*
M_1 Reliability	A_1	3.4	8.50	$r_{11} = 0.708$
	A_2	2.5	2.50	$r_{21} = 0.208$
	A_3	–	1.00	$r_{31} = 0.084$

r_{ij} = Effectiveness of alternative i with respect to measure j.

Figure 3. Derivation of Ratings, r_{ij} with Respect to Effectiveness Measure, M_1

a ratio, the degree to which one alternative is superior to another in terms of its effectiveness with respect to the measure being considered.

For example, assume in the comparison being considered, that in terms of reliability, system A_2 is judged to be 2.5 times more effective than alternative A_3 and alternative A_1 is judged to be 3.4 times more effective than alternative A_2. These judgments are entered into the table as shown in Figure 3. By appropriate multiplication of these values, the relative effectiveness of each alternative with respect to the last alternative on the list (A_3) is calculated; each of these numbers is then averaged by dividing by their sum. The averaged ratings are then listed in the fifth column as shown in Figure 3, and are the respective ratings of the three alternative systems in terms of reliability. The motivation for averaging these ratings will become obvious shortly.

The above procedure is then repeated for the other two measures of effectiveness (weight and size); the reader is now referred to Figure 4. For example, system A_2 in terms of weight is considered to be twice as effective as system A_3, and A_1 is considered to be only 9/10 as effective as system A_2. Similarly with respect to size, system A_2 is considered to be only 1/2 as effective as system A_3; system A_1 is considered to be only 1/2 as effective as system A_2. Respective ratings are calculated according to the procedure outlined previously and are summarized in Figure 4. It should now be obvious that the reason for averaging the ratings is to put all of the ratings derived for the various measures of effectiveness on the same basis, i.e., in the range of zero to one. (Any other common range could be used just as well.)

Having derived the respective weights for the three measures of effectiveness and the ratings for each of the alternative systems with respect to the three measures of effectiveness, one has all of the data required to enter the calculation matrix outlined in Figure 1. The data and calculations of overall effectiveness are outlined in Figure 5. It is determined that alternative A_1 has an effectiveness of 0.573, alternative A_2

		Relative Effectiveness		
Effectiveness measures	*Alternative systems*	*With respect to next alternative*	*With respect to last alternative*	*Ratings,* r_{ij}
M_1 Reliability	A_1	3.4	8.50	$r_{11} = 0.708$
	A_2	2.5	2.50	$r_{21} = 0.208$
	A_3	—	1.00	$r_{31} = 0.084$
			$\Sigma = 12.00$	$\Sigma = 1.000$
M_2 Weight	A_1	0.9	1.80	$r_{12} = 0.375$
	A_2	2.0	2.00	$r_{22} = 0.416$
	A_3	—	1.00	$r_{32} = 0.209$
			$\Sigma = 4.80$	$\Sigma = 1.000$
M_3 Size	A_1	0.5	0.25	$r_{13} = 0.143$
	A_2	0.5	0.50	$r_{23} = 0.285$
	A_3	—	1.00	$r_{33} = 0.572$
			1.75	$\Sigma = 1.000$

Figure 4. Summary of Ratings, r_{ij}

has an effectiveness of 0.262, and alternative A_3, an effectiveness of 0.165. It should be noted that the alternatives turn out to have been ranked in the order of decreasing effectiveness purely as a matter of coincidence.

One shortcoming of the procedure is that it does not provide any means for handling risk and/or uncertainty considerations. In assessing the relative importance of a given system or effectiveness measure, it is assumed that an outcome will definitely occur. In reality, however, any given outcome or occurrence would properly be described by a probability distribution function. The above procedure will not reflect explicitly the aversion which a decision maker may feel toward either the risk or uncertainty regarding the likelihood of the actual occurrence of a given outcome. Furthermore, the process provides no mechanism for reflecting perceived tradeoffs between the effectiveness of a given outcome conditional upon actual occurrence and the variable risk or uncertainty surrounding its occurrence. This is, in some respects, an academic question since in most cases the decision maker has no information regarding the risks or uncertainty, and so could not incorporate it even if he had a procedure that, in principle, would permit him to do so. An excellent discussion of these limitations and others, along with their implications, and the general methodology of cost effectiveness is contained in a recently published textbook.[5]

	Measures of effectiveness, (M) and Relative Weights, (w)			
Alternative system concepts	M_1 *reliability* $w_1 = 0.67$	M_2 *weight* $w_2 = 0.22$	M_3 *size* $w_3 = 0.11$	*Total effectiveness* $E[A_i]$
A_1	0.708	0.375	0.143	0.573
A_2	0.208	0.416	0.285	0.262
A_3	0.084	0.209	0.572	0.165
				$\Sigma = 1.000$

$$E[A_1] = \sum_{j=1}^{3} w_j r_{1j} = (0.67) \times (0.708) + (0.22) \times (0.375) + (0.11) \times (0.143) = 0.573$$

$$E[A_2] = \sum_{j=1}^{3} w_j r_{2j} = (0.67) \times (0.208) + (0.22) \times (0.416) + (0.11) \times (0.285) = 0.262$$

$$E[A_3] = \sum_{j=1}^{3} w_j r_{3j} = (0.67) \times (0.084) + (0.22) \times (0.209) + (0.11) \times (0.572) = 0.165$$

Figure 5. Summary of effectiveness analyses

A few more comments regarding the implementation of the procedure outlined are in order. In actual practice, it is generally desirable to get the judgments of several decision makers as inputs to the procedure. This can be done in several ways. One way would have each decision maker go through the process independently and then average his final effectiveness measures for the respective alternative. Another way would use average values for each of the paired comparisons, and then conduct the evaluation using these average values.

Having arrived at a final measure of effectiveness for each of the alternatives under consideration, one can employ sensitivity analyses to explore the effect of changes in the value judgments assigned at any step in the paired comparison procedure on the final decision. The purpose of a sensitivity analysis is to identify areas where emphasis should be placed in system improvements, since one desires to concentrate on areas wherein a given level of improvement will produce the greatest improvements in overall system effectiveness.

Another dimension which can readily be incorporated into the procedure is to use several levels of the effectiveness measures. For example, within the measure of size, one may wish to consider explicitly length, width, and height. Such considerations can be factored into the procedure rather easily, and Miller[2] demonstrates a technique for doing so. Similarly, when evaluating the effectiveness of alternative systems it may on occasion be desirable to break the systems down into respective components so that explicit judgments can be made on each of the important items comprising the system. This simply adds another dimension to the decision matrix but poses no conceptual problems. This degree of sophistication was not warranted for the analyses reported in this paper.

Process Alternatives

A complete technical description of the process alternatives (biological and chemical) available in various packaged waste treatment plants is not germane to the cost-effectivenss methodology described in this paper; readers are referred to an earlier publication[6] for a general discussion of different treatment processes, along with a description of the manufacturers' variations available within each category. For descriptions of an oxidation pond, aerated lagoon and oxidation ditch, four additional sources may be consulted.[7,8,9,10]

Evaluation of Commercially Available Systems

TECHNICAL REQUIREMENTS

Technical requirements used to select various biological and chemical systems for evaluation are summarized below. These requirements were treated as minimum performance criteria; commercially available systems failing to meet all of these standards were excluded from the intensive cost-effectiveness analysis.

- Environment: All but polar
- Camp Population: 500 and 1000 men
- Waste Loading:
    - Hydraulic: 65 gal/man/day
        - Total: 500-man camp—32,500 gal/day
        - Total: 100-man camp—65,000 gal/day
    - Organic (BOD:) 400 milligrams/liter
    - Suspended Solids: 400 milligrams/liter
    - Sludge Quantities: Dry weight—500-man camp—92 lb/day
        - 1000-man camp—184 lb/day
        - Volume—500-man camp—400 gal/day
        - 1000-man camp—800 gal/day

- Degree of Treatment Required: Secondary treatment or equivalent (80 percent or more BOD and suspended solids removal)
- Equipment Life: 5 years
- Maximum Size of Shipment Packages: 8 X 8 X 20 ft
- Maximum Weight of Shipment Packages: 25,000 lb

Based upon a survey of 52 manufacturers 15 different process systems were found to meet the minimum performance criteria outlined above.

COST EVALUATIONS

Summary of Cost Criteria

Specific cost parameters and assumptions are outlined below:

- Capital cost amortization parameters
  - Interest rate: 5 percent
  - Equipment life: 5 years
- Manpower: $10.25/hr (total cost to support Second Class Petty Officer in the field)
- Power: $0.05/kwh (includes amortized capital cost of equipment, shipping of equipment and fuel to Southeast Asia, the cost of shelter or housing for equipment and allowance for power–transmission system)
- Shipping: $1.00/cu ft (U.S.A. to Southeast Asia—assumed to be independent of weight)
- Earthwork:
  - Site preparation: $80/1,000 sq yd
  - General excavation: $550/1,000 cu yd

Two sets of cost estimates were developed for all systems investigated; one for the capital investment required to install the complete system at the job site, and the other for operating the plant in the manner specified by the manufacturer. For evaluation purposes, both of these costs were reduced to equivalent annual costs and unit costs (dollars/1000 gallons).

Unit Capital Cost Data. The unit capital cost ($/1000 gallons) was obtained from the annual capital cost data and the average quantity of waste water treated annually. For the annual capital cost, the total capital cost is amortized over 5 years at an interest rate of 5 percent.

Unit Operating Cost Data. The unit operating cost ($/1000 gallons) was estimated from the annual operating cost data and the average plant flow rate. The annual operating cost includes the cost of chemicals, equipment, repairs, power, and general operating maintenance labor. Allowances for supervisory staff and overhead items are not included since these cost items are difficult to define for a military combat situation.

EFFECTIVENESS EVALUATION

Measures of Effectiveness

As indicated, the first step in applying the decision model outlined above is to develop the effectiveness criteria and to derive their relative weights. Eight effectiveness measures were identified. Using the technique of paired comparisons outlined earlier, relative weights for each were calculated; these are summarized in Table 1. Some discussion of what is meant by each measure of effectiveness will also be instructive.

Table 1. Effectiveness Criteria and Adjusted Relative Weights

	Effectiveness Measures	*Adjusted Relative Weights*
M_1	Simplicity of Operation	0.37
M_2	Simplicity of Installation	0.25
M_3	Operational Flexibility and Reliability	0.13
M_4	Environmental Quality Control	0.10
M_5	Manpower Requirements	0.06
M_6	Space Requirements	0.04
M_7	Power Requirements	0.03
M_8	Relocatability	0.02
		1.00

M_1–Simplicity of Operation. To minimize routine daily demands on manpower and other resources, operational simplicity is of paramount importance. Specific items to be considered include the degree of skill needed to operate and maintain the system, the frequency of laboratory tests and/or other monitoring activities required, the extent of automatic *versus* manual controls, and general housekeeping requirements.

For automatic controls, the following position was taken. In situations where automatic controls are auxiliary to manual controls, they are considered to be an advantage. In situations, however, where automatic controls are a substitute for manual controls, a low ranking is assigned.

M_2–Simplicity of Installation/Construction. After simplicity of operation, simplicity of installation and construction is considered to be the next most important feature. Here one is concerned with such things as the extent of field construction required (concrete base, excavation, heavy equipment needed, etc.) and the degree of field assembly required in terms of the number and ease of required field connections (welded versus nut and bolt). One factor which contributes significantly to field assembly considerations, is that in order to meet the 8 X 8 X 20 ft shipment package size constraint, several manufacturers indicated a need to cut their equipment into pieces which would have to be refabricated on site. The extent of this varies considerably from one manufacturer to another and from one system to another.

M_3–Operational Flexibility and Reliability. Because of the changing activities in military operations and the sporadic availability of manpower and spare parts, operational flexibility and reliability is an important factor to be considered in the selection of advanced-base waste water treatment and disposal systems. Items of concern here are the ability of a system to perform satisfactorily under varying hydraulic and organic loading and the extent of process controls available for the control of air rate, return sludge, etc.

It should also be noted that significant differences also exist within a specific group of packaged plants in that the operational flexibility and reliability of two smaller systems, each designed to treat one-half the total flow, is considered to be greater than that for a single large system.

M_4–Environmental Quality Control. Environmental quality control is important for health and aesthetic reasons which in turn directly affect troop morale and effectiveness. All systems evaluated meet the minimum basic technical requirement of equivalent secondary treatment established previously. Environmental control factors over and above the minimum requirements are given due consideration in the overall system evaluations. Items of concern here are degree of treatment over and above secondary treatment, adequate handling and disposal of sludge, expected odor problems, the potential of surface and subsurface water pollution, etc.

M_5–Manpower Requirements. Manpower requirements refer to the manpower required to construct and operate a given system. Although it is true that differences in manpower requirements will also be reflected in the cost analysis, it is felt that because manpower is a limited resource, manpower needs contain dimensions over and above cost that relate purely to effectiveness.

Consider, for example two hypothetical systems, the total combined operating and capital costs of which are equal, but one system requires less manpower than the other. Since manpower is a prime resource at advanced bases, the system requiring less labor should receive more favorable overall evaluation (in spite of the fact that the two systems compare equally in terms of cost and other performance characteristics) besides what would be reflected in the labor-dollar-cost analysis. Considerations such as these are incorporated in the effectiveness portion of the analysis.

For purposes of comparing individual systems, primary importance was attached to low operating labor requirements. There are two reasons for this. First, operating labor is a continual requirement whereas construction labor is a "one shot" demand. Additionally, military forces find it more difficult to provide personnel with operational skills than those with construction skills. Thus in the system evaluations the systems which received the highest ratings were those with the lowest operating labor requirements. Differences in construction labor requirements were used only to break ties between separate systems with identical operating-labor requirements.

M_6–Space Requirements. The land area required for a given system determines the space required. For security reasons it is desirable to maintain military systems and supporting facilities in as confined an area as possible.

M_7–Power Requirements. Electrical energy and/or fuel needed to operate a given system are included in Power Requirements. As in the case of manpower needs, low power requirements will reflect favorably in the cost analysis, but since power is a limited resource, low power requirements also contain dimensions which relate purely to effectiveness. Generally speaking, the relative effectiveness of the various systems with respect to power needs was considered inversely proportional to the absolute power required. For example, a system requiring 7 kw to operate was considered (in terms of power requirements) to be twice as good as one requiring 14 kw.

M_8–Relocatability. Due to the constantly changing demands on military forces, especially under combat conditions, there is some merit in having military hardware and supporting systems (such as waste water treatment plants) that are easily transportable. To reflect this factor in the evaluations conducted, systems which would require extensive disassembly, refabrication, and reinstallation to be moved were rated lower than those which could be transported essentially intact.

RESULTS

A total of 15 different treatment systems met the minimum performance criteria set forth earlier. These systems are given in Table 2. All were included in cost-effectiveness evaluation.

Table 2. Summary of Treatment Systems Used in Cost-Effectiveness Evaluation

Treatment Process	*Number of Systems*
Biological Process	
Aerated lagoon	1
Completely mixed activated sludge	2
Contact stabilization	2
Extended aeration	3
Oxidation ditch	1
Oxidation pond	1
Rotating biological contactor	1
Trickling filter	1
Ultrafiltration	1
Chemical Processes	
Chemical precipitation	1
Electrochemical flotation	1
Total	15

Results of the cost and effectiveness evaluations for 500- and 1000-man systems are summarized in Tables 3 and 4. Since there are 15 potentially feasible alternative systems available for both 500- and 1000-man camps, perception of the cost effectiveness tradeoffs, and identification of the most cost effective systems from these tabular data is rather difficult.

To facilitate the identification of the most cost-effective systems, Figures 6 and 7 were prepared. These figures represent graphically the relationship between total unit costs (capital plus operating) and total effectiveness for the various systems. It can be ascertained visually, from these figures, that waste treatment processes designated A_8, A_9, A_{10}, A_{11}, A_{12}, and A_{14} are the most cost-effective systems in the entire group. This is true for both 500- and 1000-man systems. This may be determined by using the following decision rule. If any system, e.g., A_i, has a greater cost but lesser or equal effectiveness than any other system, i.e., A_j, A_i is eliminated. Repeated applications of this elimination procedure leaves systems $A_8, A_9, A_{10}, A_{11}, A_{12}$, and A_{14}.

A critical inspection of Figures 6 and 7 indicates that A_{10} is the least costly of all systems but is also the least effective; system A_{12}, although having the highest effectiveness, is also most expensive. The curve possesses two distinct ranges, one below and the other above system A_8. The range

Table 3. Summary of Cost-Effectiveness Analysis—Alternative Treatment Processes for 500-Man Camps

	Measure of Effectiveness, (M_j), and Relative Weight, (w_j)[a]									
Alternative Systems A_i	M_1 *(0.37)*	M_2 *(0.25)*	M_3 *(0.13)*	M_4 *(0.10)*	M_5 *(0.06)*	M_6 *(0.04)*	M_7 *(0.03)*	M_8 *(0.02)*	*Total Effectiveness, $E(A_i)$*	*Total Unit Treatment Cost, \$/1000 gal*
A_1	0.0303[b]	0.0133	0.0109	0.0010	0.0034	0.0004	0.0040	0.0010	0.0643	0.53
A_2	0.0303	0.0133	0.0109	0.0010	0.0034	0.0004	0.0024	0.0010	0.0627	0.60
A_3	0.0228	0.0140	0.0077	0.0097	0.0026	0.0035	0.0013	0.0011	0.0627	1.05
A_4	0.0228	0.0140	0.0077	0.0097	0.0023	0.0035	0.0007	0.0011	0.0618	1.70
A_5	0.0228	0.0140	0.0077	0.0097	0.0033	0.0035	0.0011	0.0011	0.0632	1.05
A_6	0.0228	0.0140	0.0077	0.0097	0.0030	0.0035	0.0016	0.0012	0.0635	1.03
A_7	0.0251	0.0140	0.0090	0.0097	0.0047	0.0035	0.0016	0.0012	0.0687	0.85
A_8	0.0251	0.0182	0.0090	0.0065	0.0037	0.0035	0.0031	0.0018	0.0709	0.60
A_9	0.0313	0.0111	0.0105	0.0020	0.0055	0.0069	0.0024	0.0009	0.0706	0.70
A_{10}	0.0331	0.0127	0.0114	0.0003	0.0035	0.0001	0.0050	0.0009	0.0670	0.39
A_{11}	0.0289	0.0191	0.0077	0.0015	0.0064	0.0035	0.0046	0.0014	0.0731	1.09
A_{12}	0.0207	0.0241	0.0081	0.0097	0.0049	0.0035	0.0004	0.0020	0.0734	1.30
A_{13}	0.0178	0.0202	0.0067	0.0097	0.0040	0.0035	0.0003	0.0014	0.0636	2.90
A_{14}	0.0187	0.0241	0.0070	0.0097	0.0058	0.0035	0.0013	0.0020	0.0721	0.93
A_{15}	0.0178	0.0241	0.0067	0.0097	0.0040	0.0035	0.0003	0.0020	0.0681	2.48

[a] Relative weights are given in parentheses and are obtained from Table 1.

[b] All matrix entries are products of respective ratings and averaged relative weights.

Table 4. Summary of Cost-Effectiveness Analysis—Alternative Treatment Processes for 1000-Man Camp

	Measure of Effectiveness, (M_j), and Relative Weight, (w_j)[a]									
Alternative System (A_i)	M_1 (0.37)	M_2 (0.25)	M_3 (0.13)	M_4 (0.10)	M_5 (0.06)	M_6 (0.04)	M_7 (0.03)	M_8 (0.02)	Total Effectiveness, $E(A_i)$	Total Unit Treatment Cost, \$/1000 gal
A_1	0.0303[b]	0.0132	0.0109	0.0010	0.0032	0.0004	0.0039	0.0010	0.0639	0.47
A_2	0.0303	0.0132	0.0109	0.0010	0.0032	0.0004	0.0021	0.0010	0.0621	0.51
A_3	0.0228	0.0140	0.0077	0.0097	0.0032	0.0035	0.0014	0.0011	0.0634	0.83
A_4	0.0228	0.0140	0.0077	0.0097	0.0022	0.0035	0.0007	0.0011	0.0627	1.47
A_5	0.0228	0.0140	0.0077	0.0097	0.0037	0.0035	0.0012	0.0011	0.0637	0.75
A_6	0.0228	0.0140	0.0077	0.0097	0.0035	0.0035	0.0017	0.0011	0.0640	0.77
A_7	0.0252	0.0140	0.0090	0.0097	0.0050	0.0035	0.0022	0.0012	0.0698	0.70
A_8	0.0252	0.0182	0.0090	0.0065	0.0033	0.0035	0.0032	0.0018	0.0707	0.46
A_9	0.0314	0.0110	0.0105	0.0020	0.0038	0.0069	0.0017	0.0009	0.0682	0.58
A_{10}	0.0331	0.0128	0.0114	0.0003	0.0029	0.0001	0.0047	0.0009	0.0661	0.31
A_{11}	0.0288	0.0190	0.0077	0.0015	0.0067	0.0035	0.0043	0.0014	0.0729	0.85
A_{12}	0.0206	0.0241	0.0081	0.0097	0.0053	0.0035	0.0005	0.0020	0.0738	1.04
A_{13}	0.0178	0.0202	0.0065	0.0097	0.0046	0.0035	0.0003	0.0014	0.0640	2.22
A_{14}	0.0187	0.0242	0.0070	0.0097	0.0061	0.0035	0.0014	0.0020	0.0726	0.80
A_{15}	0.0178	0.0292	0.0067	0.0097	0.0024	0.0035	0.0003	0.0020	0.0716	2.48

[a] Relative weights are given in parentheses and are obtained from Table 1.

[b] All matrix entries are product of respective rating and normalized relative weights.

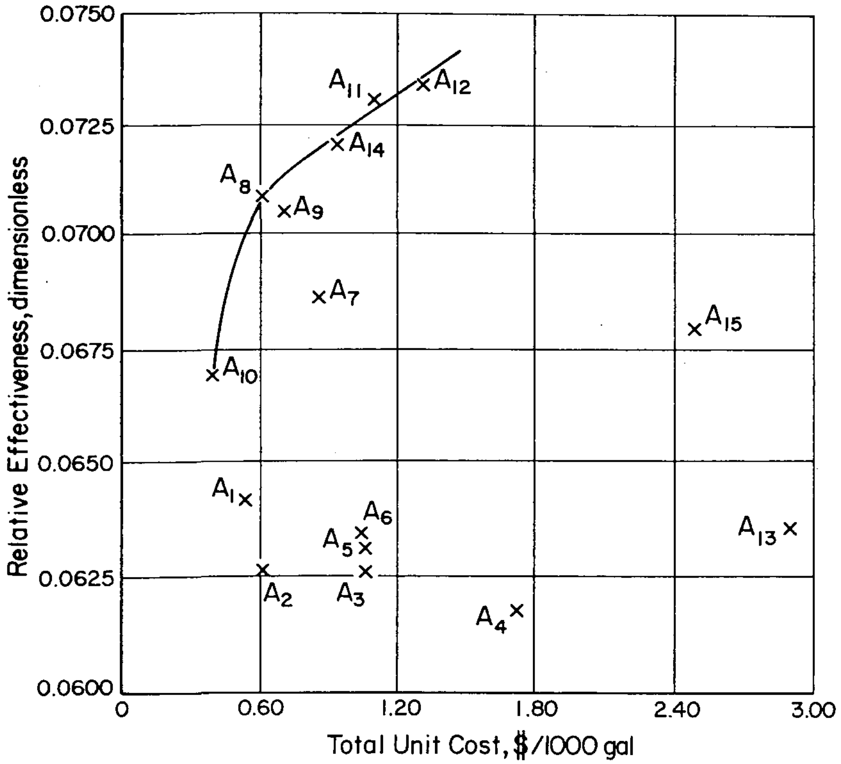

Figure 6. Relationship between total unit cost and total relative effectiveness of various alternative treatment systems suitable for installation at 500-man camps

below system A_8 has higher slope than that above, indicating that systems in the lower range yield a greater gain in effectiveness for any given incremental cost than do systems in the range above system A_8. The sharp change in the slope at system A_8 is a break point, indicating that the system is highly cost effective as compared to the others. Other alternative systems such as A_{14}, A_{11}, and A_{12} exhibit a nearly linear relationship between cost and effectiveness. Selection of any of these systems would depend upon how much one can afford to pay for the additional effectiveness gained.

Results of this study have provided the Navy with guidance in terms of waste management systems that should be selected for use at advanced bases. Furthermore, this study is one example of how systems technology can be adapted to the solution of complex environmental quality management problems.

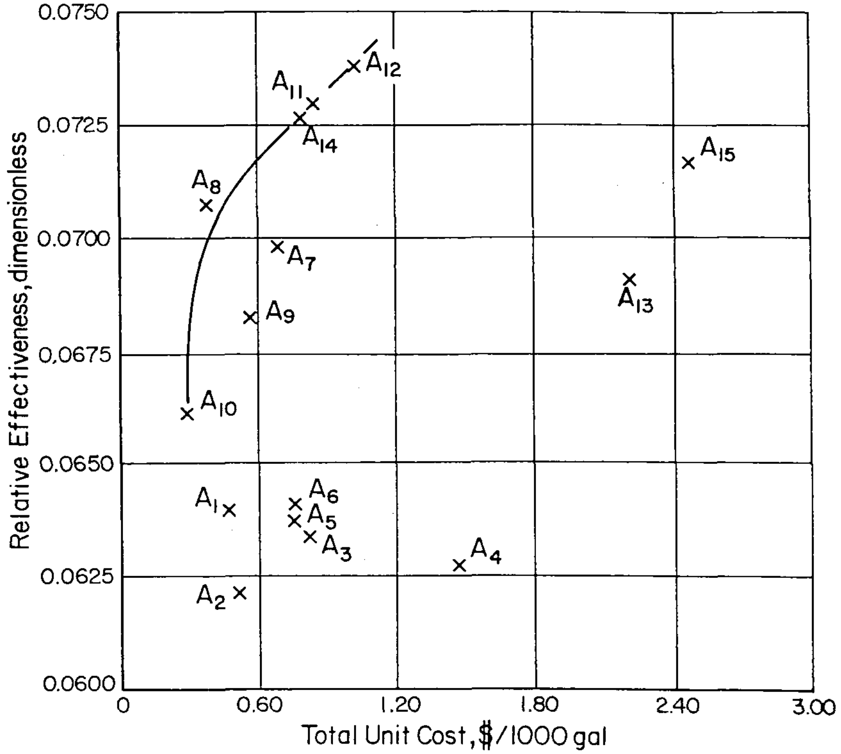

Figure 7. Relationship between total unit cost and total relative effectiveness of various alternative treatment systems suitable for installation at 1000-man camps

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