# An Approach to the Economic Analysis of Solid Waste Disposal Alternatives

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# Abstract

In this paper a mixed integer optimization approach to the selection of sanitary landfill site sizes and locations in a regional context is explained and illustrated using stylized cost and location information adapted from a real case study. The rationale for the exercise is that individual solid waste disposal site investments should not be viewed in isolation from the spatial setting and their cost relationships with other sites in a regional system, because ignoring these relationships is likely to raise system operating and capital costs. But, because it is difficult to sort through and prioritize disposal alternatives by inspection or repeated simulation of the total costs of all possible combinations of sites and scales when the region is "large", a least-cost optimization method is recommended which does the sorting automatically once the problem has been properly specified.

After reviewing the basics of the heuristic approach to solid waste disposal site selection, the optimization model is laid out and solved in the case study context, initially in terms of financial costs. In a subsequent section, a way of incorporating the relative environmental damages of alternative locations into the model is suggested, and the example is re-solved with environmental costs included to show how they can influence the identification of the best set of sites. Suggestions about model refinements appear in a concluding section.

The text assumes the reader is familiar with economic activity analysis and non-market valuation techniques.

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# Introduction

## The General Problem

The municipal solid waste disposal problem is one of finding the disposal technologies (landfill, incinerator), facility sizes and site locations that minimize system cost. If the scope of the geographic problem-shed is defined broadly, there potentially can be a large number of places to dispose of solid waste generated by residents of rural communities and metropolitan areas. Each possible disposal location may be developed accommodate different annual amounts of waste, and, because of economies of scale[1], the larger the size of a landfill or an incinerator, the lower the average annualized disposal cost per ton.

In a world without transportation costs (and community protest), the obvious least cost result in the presence of economies of scale would be one mammoth site handling the solid waste from all jurisdictions. However, the existence of waste haulage costs complicates the issue. Beyond a certain haulage distance the increase in transport cost from some waste generation points to a single large disposal facility may more than offset the fall in disposal cost per ton associated with accommodating the extra waste, making it more economical to build additional disposal facilities to save on waste transport costs. When there are many generation points and a number of alternative site locations, the site selection and transport routing problem rapidly becomes quite complicated. At the opposite extreme, the balkanized, computationally trivial solution of placing a disposal site in each political jurisdiction or metropolitan area, independent of the amount of waste each generates, would not be optimal since economies of scale could not be exploited, and systemwide costs would not be minimized.

In addition to the financial costs of waste disposal, there are potential regional impacts on public good resources and local environmental costs that should also be considered. At the regional level, disposal sites may produce negative effects on watersheds, aquifers, woodlands, and wetlands. Local negative impacts include traffic congestion, odor, noise, air pollution and the community health risks posed by a disposal site.

The general problem, therefore, is to design a regional waste disposal system that minimizes social costs, subject to the technological, health, and safety regulations of the site permitting authority. Social costs include both financial costs and the monetary equivalent of the environmental and public good damages each site imposes. Symbolically (Swallow, Opaluch and Weaver 1992) the problem can be expressed as:

$$\min_{J} FC(J) + EC(J), \quad \textit{where} \quad J \in \Omega$$

subject to $HS(J) \geq 0$,

where J represents a vector of characteristics describing a site; FC(J) are the out-of-pocket costs for site development and operation, inclusive of transportation; EC(J) is a money measure of local and regional environmental damages associated with choosing site J; $\Omega$ represents the universe of possible sites; and HS(J) are technological, health and safety constraints.

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[1] Under economies of scale, average long run output cost (in this case output is the waste disposed of) falls as the level of operation increases. Dooley et. al. (Fourth Quarter 1994, p.20) explain that fixed costs per unit associated with land acquisition, permits and licenses, buildings, erosion control and construction management fall with increasing landfill size. In addition, larger landfills have lower per unit operating costs for labor, equipment maintenance, operation of the leachate collection system, and well monitoring.

## The Role of Cost-Benefit Analysis

There are basically two different functions of economic analysis. The most familiar, perhaps, is to help decide whether to go ahead with a project or not (or, in its weaker form, to justify going ahead). The second is to help design a project to accomplish its stated objectives in the most efficient way. Benefit-cost analysis, if artfully employed, can be (but rarely is) used to serve both purposes, while least cost analysis takes the decision to go ahead with the project as given (Vaughan and Ardila 1993). In the particular case of solid waste disposal we would argue that the least cost design question is logically prior to, and perhaps more relevant than, a benefit/cost analysis that takes the design as exogenously given and attempts to justify the project based on estimates of consumer willingness to pay for better service and safer disposal elicited from users who can also entertain the possibility of illegal dumping at near zero cost. The working assumption in this paper therefore is that the social benefits of sanitary, rather than unregulated, disposal outweigh the social costs, so the question becomes one of using economic analysis to find the optimal (least cost) system configuration.

## Structure of the Paper

In this paper a mixed integer regional optimization approach to disposal site size and location selection, based on Dooley et. al. (1993), is explained and illustrated using stylized cost and location information adapted from a real case study.[2] The rationale for the exercise is that individual solid waste disposal site investments should not be viewed in isolation from the spatial setting and their cost relationships with other sites in a regional system, because ignoring these relationships is likely to raise system operating and capital costs. But, because it is difficult to sort through and prioritize disposal alternatives by inspection or repeated simulation of the total costs of all possible combinations of sites and scales when the region is "large", an optimization method is recommended which does the sorting automatically once the problem has been properly specified.

After reviewing the basics of the heuristic approach to site selection, the optimization model is laid out and solved, initially in terms of financial costs (FC(J) above). In a subsequent section, a way of incorporating the relative environmental damages of alternative locations into the model (based on Swallow et. al. 1992, 1994 and Opaluch et. al. 1993) is explained, and the example is re-solved with environmental costs included (EC(J) above) to show how they can influence the identification of the best set of sites. Suggestions about model refinements appear in a concluding section.

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[2] The information used herein draws from the problem analyzed by Norconsult (October 1996) in their suggested plan for a solid waste management system in Jamaica. While the basic information used in this paper is based on engineering data, the several shortcuts and simplifications undertaken to make our stylized illustration more easily understood mean that the results are not definitive and have not been verified or endorsed by either the Government of Jamaica, the IDB, or Norconsult.

# Solution Approaches

There are several steps involved in identifying and screening disposal sites, most of which require engineering expertise. These steps provide the data needed for either an ad-hoc search of the possibilities or a more structured economic modeling approach. For instance, Box 1 below contains the standard steps in site selection recommended by an engineering text.

**Box 1: Site Selection**

"Selection of a sanitary landfill site is often more a socio-political process than an engineering process. The selection process should involve the evaluation of at least two potential sites within the study area. A typical site-selection scenario would be as follows:

> *Accumulate Available Data.* Land use maps, topographic maps, water well logs, soil conservation service soil maps, highway maps, and bridge loading information should all be used in the study.
>
> *Establish Minimum Site Size*. The geometry of the site is very important. Required setbacks from roads and other natural features make portions of a site unusable. A square site maximizes the amount of land available for actual solid waste disposal activity....
>
> *Obtain Soil Borings*. Soil borings are required on the most desirable of the sites. ...
>
> *Prepare Budgetary Cost Estimate*. Budgetary cost estimates must be prepared for each of the selected sites. The cost estimates must be of sufficient detail to allow a comparison among the various sites. The capital cost items must be on an annual basis. Items included in the cost estimates should be

- Land cost
- On-site development costs (roads, fences, leachate control, liners, etc.)
- Off-site costs (bringing access roads up to anticipated load-carrying capacity)
- Cost of closing the site when it is filled
- Cost of perpetual care for the site, including transportation and treatment of any leachate
- Anticipated annual operating cost

The total annual cost should be reduced to a cost-per-ton figure.The site with the lowest cost per ton is not necessarily the best site. Transportation costs for getting the solid waste to a remote site are considerable. This cost should be computed before any decision is made....

> *Select the Most Desirable Site.* Barring any political or social constraints, the site recommended should be the one with the lowest cost (trucking plus disposal) per ton."

**Source**: Robert A. Corbitt. 1990. *Standard Handbook of Environmental Engineering.*New York: McGraw-Hill. p. 8.119

### Screening, Scoring, and Brute Force Selection

In the LAC region, some countries have developed detailed regulations specifying the minimally acceptable technical criteria for a sanitary landfill, while others have not (OPS 1995; Acurio et. al. 1997 Cuadro 3.1.5). In general, there are widespread solid waste management deficiencies; in a sample of major cities surveyed by Acurio et. al. 30% of the disposal sites were sanitary landfills, 35% were "semi-controlled", and the remaining 35% were open dumps. This distribution may be misleadingly optimistic because Acurio et. al. caution that the classification of "sanitary" may not be in conformity with the strict meaning of the word, and in smaller cities the situation is likely to be worse than it is in the major urban centers.[3]

In countries where technical norms exist and are vigorously enforced[4] they can be used to screen out unacceptable locations in the original scoping stage or entered as constraints in the programming model described below to achieve the same effect.[5] If one is inclined to accept the norms as economically justified, either of these approaches has merit. Where no norms exist in certain dimensions and the application of developed-country standards in their stead would impose inordinate costs, more flexible approaches may be warranted. One alternative is to categorize sites by qualitative levels of suitability, as in Table 1 below.

Candidate sites can be screened, often in a sequence of elimination rounds, to narrow the field, discarding those that are obviously unsuitable. Point scoring methods can be used to rank alternatives and isolate infeasible sites; a simplified example of the scoring technique is shown in Table 2 below. Scoring approaches have been used to develop some IDB projects.[6]

If the selection were being done for just one metropolitan area, and there were only two possible sites, the procedure illustrated in Table 2 could lead to a decision fairly easily. In a regional planning context, however, the subset of feasible candidate sites left after ranking or preliminary screening is still likely to be much larger than the unique combination that minimizes system cost.

One way to find the optimal combination among the feasible candidates is by brute force, enumerating every plausible combination of waste generating jurisdictions and landfill locations (each over a range of sizes). The aggregate system costs (transportation, investment, and operating expense) of each combination would each have to be independently calculated, and the costs of all combinations inspected to find the least cost configuration.

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[3] The American Society of Civil Engineers defines a sanitary landfill as "a method of disposing of refuse on land without creating nuisances or hazards to public health or safety, by utilizing the principles of engineering to confine the refuse to the smallest practical area, to reduce it to the smallest practical volume, and to cover it with a layer of earth at the conclusion of each day's operation or at such more frequent intervals as may be necessary." (USEPA, November 1989, p. 108). For a more detailed characterization of the differences between open dumps, controlled dumps, and sanitary landfills see Rosenberg (1996), p. 93.

[4] A lack of enforcement is evidence that the de jure norm is perhaps not regarded as consistent with society's appreciation of the net benefits of environmental protection at that level rather than at the observed de-facto norm. Some balancing of costs and benefits of mitigation may be required in such situations. See below.

[5] To keep the size of the model manageable, it generally would be preferable to screen out obviously unacceptable sites a-priori and accept the design criteria and costs provided by the engineers for feasible sites as givens for the economic analysis (e.g. in the United States, the U.S. Environmental Protection Agency 's Municipal Solid Waste Landfill (MSWLF) criteria issued in 1991 contain strict regulations regarding sites located at, on, or near airports, flood plains, wetlands, fault areas etc.). Alternatively, the programming model could be expanded to incorporate mitigation measures as decision variables (e.g.. liners, leachate collection systems, berms and grading, methane collection) to allow the choice of such activities to avoid violation of environmental constraints. In our case study demonstration appearing below the former, simpler, route is taken.

[6] For example, one Terms of Reference for a solid waste management program feasibility study required the consultant to "...develop a point system for grading projects corresponding to the various geographic areas on the basis of their cost-effectiveness, economic impact, and social and environmental impact."

**Table 1. Brazilian Criteria for Evaluation of Sanitary Landfill Sites**

| Criterion | Recommended | Recommended with Restrictions | Not Recommended |
|---|---|---|---|
| Useful life | More than 10 years | 10 years | .... |
| Zoning-environmental | Areas without environmental zoning restrictions | Areas without environmental zoning restrictions | Environmental conservation or related areas |
| Zoning--urban | Low growth rate | Intermediate growth rate | High growth rate |
| Population density | Low | Medium | High |
| Land use | Undeveloped or public land | Undeveloped or public land | Highly developed |
| Land value | Low | Medium | High |
| Acceptance by the community and environmental NGOs | Good | Fair | Opposed |
| Distance from watercourses |  | Less than 200 meters, with approval of responsible environmental authority | Less than 200 meters, with approval of responsible environmental authority |

Source: Jardim and Wells (1995). Authors' translation/adaptation.

**Table 2. Ranking Potential Landfill Sites by Scoring**

| Site | Criteria | Score: High=3; Med.=2; Low=1 | Total Score |
|---|---|---|---|
| Site # 1 | potential capacity | 1-less than 5 years estimated use |  |
|  | public acceptability (NIMBY) | 1-high opposition |  |
|  | hydro-geology | 3-low conductivity, low water table |  |
|  | cost | 3.-low prep., little lining required |  |
|  | other siting considerations | 1-close to airport | **9 Points** |
| Site # 2 | potential capacity | 3-over 10 years estimated use |  |
|  | public acceptability (NIMBY) | 2-strong but negotiable opposition |  |
|  | hydro-geology | 2-low conductivity, high water table |  |
|  | cost | 2-high prep., medium lining |  |
|  | other siting considerations | 2-accessible to other parts of city | **11 Points** |

Note: NIMBY refers to "Not in my backyard" opposition. The example uses equal weights for different criteria. Planners may elect to use unequal weights.

Source: Rosenberg (1996), p. 97.

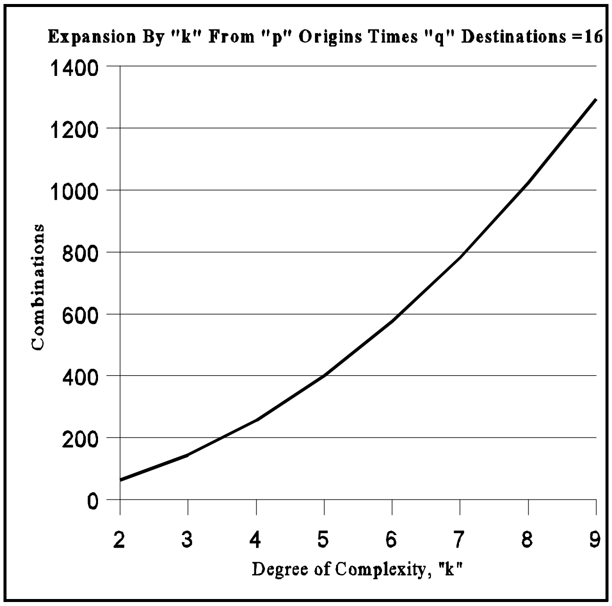

**Figure 1**. **Origin/Destination/Size Combinations**

The repeated cost calculation approach can rapidly become quite burdensome. For instance, Figure 1 shows that with just 2 waste-generating jurisdictions, 4 feasible disposal locations and 2 alternative landfill capacities at each disposal location, the number of combinations that theoretically would have to be separately costed out and inspected is only 16. But a doubling of the number of locations and disposal possibilities (4 jurisdictions, 8 landfill locations and 2 sizes) requires 64 separate cost calculations, a tripling requires 144, and so forth.[7]

In their application to North Dakota, Dooley et. al. 1993 had 179 wastesheds (*p*), 59 potential sites (*q*), and 5 alternative landfill sizes at each site (*r*), implying that $p \bullet q \bullet r$=53,805 combinations would have to be costed and sorted under the brute force approach; obviously an impossible task. Even after eliminating waste origin-landfill destination possibilities that involved round-trip waste transport of over 200 miles, Dooley et. al. were still left with 7000 combinations, which they didn't have to cost separately because they applied an optimization approach instead. Our case study example explained below is on the borderline of being manageable by brute force, with 13 waste centroid origins, 9 possible destinations, and 4 facility sizes, giving 468 potential combinations. The consulting firm that prepared the feasibility study upon which our case study example is based (Norconsult,October 1996) did, in fact, solve it by brute force. The optimization approach explained below is more computationally efficient and less error-prone than repeated trial and error under the brute force approach, especially for large problems.

## A Mixed Integer Programming Approach: Optimal Landfill Site Selection

**Mixed Integer Programming** Like a standard linear programming problem, mixed integer programming (MIP) involves the solution of a constrained optimization problem (cost minimization, profit maximization) where the objective function is linear in the activity levels (i.e., variables). But, in mixed integer programming, some variables are restricted to take on only integer or whole-number values (often 0=don't do; 1=do), while others are allowed to be either integers or fractions, as in linear programming. Integer variables are a convenient way to deal with fixed charge problems like facility investment, where there is an initial capital outlay that is the integer variable and a subsequent operating level of the facility with a unit variable cost which is a continuous variable. Integer variables are also a good way to handle multiple choice problems where only one of several standard equipment capacity sizes can be built (Driebeek 1969).

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[7] This is just an application of the fundamental principle of permutations and combinations that if one thing can be done in *p* different ways, a second thing in *q* different ways, and a third in *r* different ways, then the number of different ways in which all the things can be done is the product of $p \bullet q \bullet r$.. When the original number of *p* and *q* possibilities is multiplied by an arbitrary factor, *k* (equal to 1, 2 and 3 in the text example), holding *r* constant, we have $k \bullet p \bullet k \bullet q \bullet r$, or $k^2 \bullet p \bullet q \bullet r$, whose derivative w.r.t. a unit change in the expansion factor *k* is $2 \bullet k \bullet p \bullet q \bullet r$. This is why the product increases nonlinearly with *k*. (i.e. increases at an increasing rate that is a multiple 2 $p \bullet q \bullet r$ of *k*).

Scale economies, which exist in solid waste disposal, cannot be captured in a standard linear programming formulation. To assign an investment cost in linear programming, one must guess a-priori about the probable capacity level that would be optimal, and enter the annualized capital cost per unit of output associated with that level into the objective function of the corresponding investment activity in the program. The undesirable implication of so doing is that it permits activities to operate at linear multiples of the base unit cost level so, for instance, doubling capacity involves doubling investment, and halving capacity halves investment. The mixed integer framework sketched below overcomes that limitation of linear programming by assigning a separate integer variable to each location and capacity alternative in the choice set, thereby incorporating scale economies and the lumpiness of investment alternatives.

## Application of Mixed Integer Programming to The Solid Waste Problem

The following mixed integer programming model is a revised[8] version of the model presented in Dooley et al 1993. The objective is to minimize the annual total out-of pocket operating and annualized investment costs of waste transport and ultimate disposal by selecting the best configuration of waste shipment assignments, landfill locations and capacities:

$$\min_{IS_{ij},GS_{kji},VS_{ij}} C = \sum_i \sum_j FC_{ij} IS_{ij} + \sum_i \sum_j VC_{ij} VS_{ij} + \sum_i \sum_k \sum_j TC_{kji} GS_{kji}$$

Cost minimization is subject to the following four sets of constraints:

$$(1)\ \sum_i \sum_j GS_{kji} \geq WASTE_k \ , \ \forall \ k$$

$$(2)\ \sum_k GS_{kji} = VS_{ij} \ , \ \forall \ i,j$$

$$(3)\ CAPACITY_i \times IS_{ij} \geq VS_{ij} \ , \ \forall \ i,j$$

$$(4)\ \sum_i IS_{ij} \leq 1 \ , \ \{0,1\} \ \forall \ j$$

where (including the dimensioning of the *i*,*j*,*k* indices used in the case study example to follow):

C = annual total investment, operating and transportation cost in Jamaica.

$FC_{ij}$ = annualized fixed cost of construction and capital equipment for a landfill of size *i* at site *j*.

$IS_{ij}$ = binary integer variable that allows for annual fixed cost of construction and capital equipment of a landfill of size *i* at site *j*.

$VC_{ij}$ = variable cost per ton of operating a landfill of size *i* at site *j*.

$VS_{ij}$ = annual number of tons transported to landfill size *i* at site *j*.

$TC_{kji}$ = cost of transporting one ton of waste from the waste generation centroid of parish *k* to landfill site *j* of size *i*.

$GS_{kji}$ = annual number of tons of waste transported from parish *k* to landfill site *j* of size *i*.

$WASTE_k$ = waste generated annually in parish *k*.

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[8] Our setup does not perfectly mimic the objective function or constraint set in Dooley et. al. (1993) because the latter appear to contain some typographical errors. We found that the model would not solve if it were configured exactly according to Dooley et. al.'s specification.

$CAPACITY_i$ = the annual amount of waste that can be accepted at a landfill size *i*. Assuming a year of 360 days:

$CAPACITY_1$ = 36,000;
$CAPACITY_2$ = 72,000;
$CAPACITY_3$ = 180,000;
$CAPACITY_4$ = 306,000.

*i* = index of possible landfill sizes (tons per day,TPD) at each site: 1 for 100 TPD; 2 for 200 TPD; 3 for 500 TPD; 4 for 850 TPD.

*j* = index of different landfill sites: 1 for St. Andrew/Kingston Metropolitan Area (KMA); 2 for Clarendon; 3 for Manchester; 4 for Westmoreland; 5 for St. James; 6 for Trelawny; 7 for St. Ann; 8 for St. Mary; 9 for Portland.

*k* = index of the waste-generation centroid of the different Parishes in Jamaica: 1 for St. Andrew; 2 for St. Catherine; 3 for Clarendon; 4 for Manchester; 5 for St. Elizabeth; 6 for Westmoreland; 7 for Hanover; 8 for St. James; 9 for Trelawny; 10 for St. Ann; 11 for St. Mary; 12 for Portland; 13 for St. Thomas.

The first constraint set above requires disposal (in one or more of the *j* landfill locations) of all the waste generated annually in each jurisdiction (Parish, in this case). Simply put, waste cannot be inventoried outside of a legitimate disposal site. The second constraint set forces the total amount of waste from all jurisdictions sent to any specific landfill of a given size (*i*) in a given place (*j*) to equal the amount of waste received at that landfill. The third set of constraints just says that the storage capacity of those landfills that are operated must equal or exceed the amount of solid waste delivered to them. Finally, the last constraint set allows only one size of landfill to be built at any site.

The model is static and represents a "typical" year of operation over the 20 year project period. The time dimension is handled by annualizing capital costs using an interest rate of 12 percent.[9] Annual waste generation quantities are estimated as the annual average of the total waste generation from the present to the terminal year, assuming a rate of growth that reflects the net effect of population growth and economical resource recovery and recycling activities, which are not endogenous in the model.

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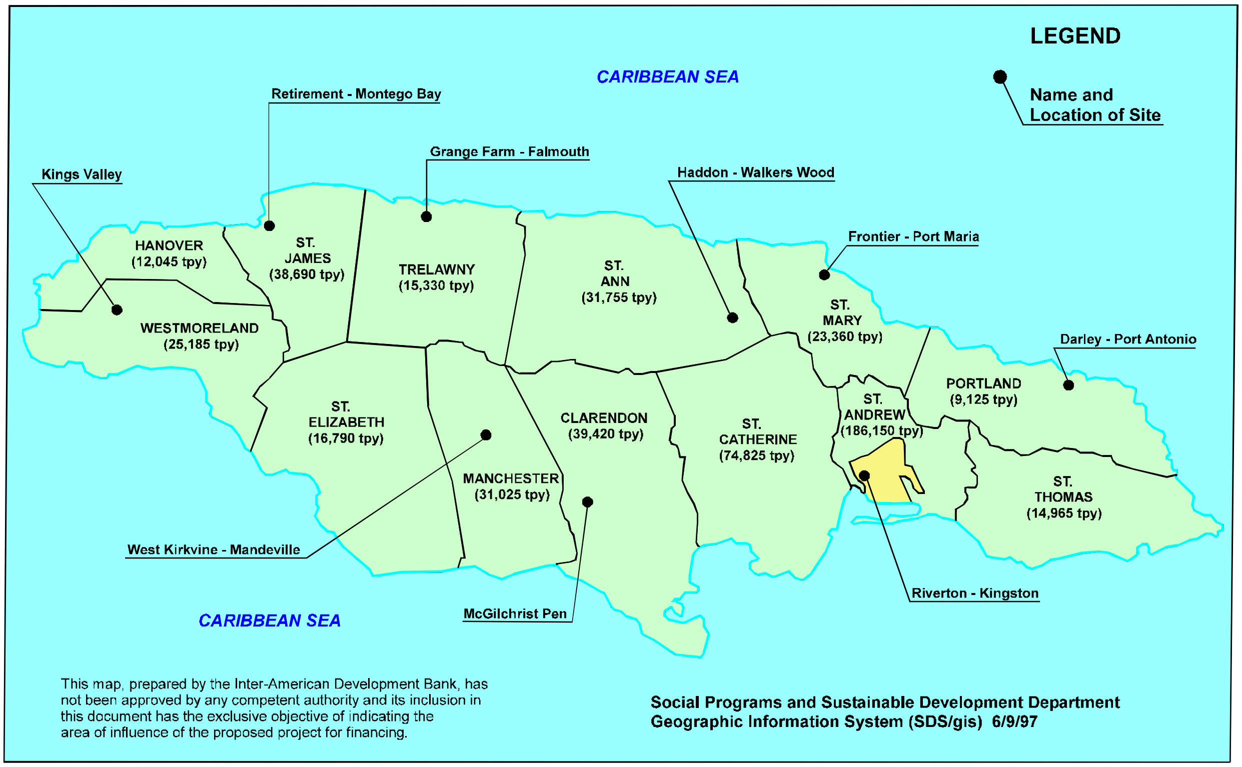
[9] That is, the present capital sum is multiplied by the capital recovery factor to convert it into a uniform annual capital cost over *n* periods. This is the future series of end-of-period payments that, like a mortgage payment, will just recover the capital sum with interest. See Table 4 and footnote 13 below.

# A Worked Example



This map, prepared by the Inter-American Development Bank, has not been approved by any competent authority and its inclusion in this document has the exclusive objective of indicating the area of influence of the proposed project for financing.

Social Programs and Sustainable Development Department
Geographic Information System (SDS/gis) 6/9/97

**Figure 2**. **Jamaica: Proposed Sanitary Landfill Sites**

### The Problem Setting

The case study is set in Jamaica, which presently does not have any sanitary landfills. Nine new landfill locations are proposed to serve the 13 Parish wastesheds on the island. Figure 2 identifies the sites, the Parishes, and their solid waste generation rates, in tons per year (tpy). To model the choice problem, waste generation points, which are located at the centroid of each Parish, have to be connected via transport distance and haulage cost to alternative landfills, whose investment and operating costs must be estimated as well.

### Wasteshed/Disposal Site Combinations and Transport Costs

Table 3 gives round-trip waste transport costs for the possibilities that are represented in the model. For example, the Trelawny site (Column #6 in the table) can either exclusively handle waste from only one Parish (its own, Kingston, or St. James), waste from all three Parishes combined, or wastes from any two out of the three suppliers (Trelawny and St. James, Trelawny and St. Andrew, or St. Andrew and St. James). Column activities do not have to be set up inside the model for all these combinations--once each generating location is connected with one or more disposal sites, the solution algorithm identifies the optimal combinations automatically. The other eight disposal sites were developed using similar logic (see the model listing presented in Annex 1).

**Table 3. Transportation Cost from Parish (k) to Landfill Site (j)** ***(1996 Jamaican Dollars per ton)***

| **To Site (j)**<br>**From Parish (k)** | (1) St. Andrew | (2) Clarendon | (3) Manchester | (4) Westmoreland | (5) St. James | (6) Trelawny | (7) St. Ann | (8) St. Mary | (9) Portland |
|---|---|---|---|---|---|---|---|---|---|
| (1) St. Andrew | 184.28 | 504.20 | 636.20 | 900.20 | 960.90 | 871.16 | 715.40 | 633.56 | 794.60 |
| (2) St. Catherine | 291.92 | 461.96 | 570.20 | | | | | | |
| (3) Clarendon | 504.20 | 291.92 | 477.80 | | | | | | |
| (4) Manchester | 636.20 | 456.68 | 225.68 | | | | | | |
| (5) St. Elizabeth | 725.96 | 549.08 | 548.60 | | | | | | |
| (6) Westmoreland | 929.20 | | | 333.32 | 654.64 | | | | |
| (7) Hanover | 1197.60 | | | 300.20 | 474.08 | | | | |
| (8) St. James | 960.90 | | | 625.64 | 242.24 | 451.40 | | | |
| (9) Trelawny | 1010.16 | | | | 465.80 | 233.96 | | | |
| (10) St. Ann | 715.40 | | | | 620.36 | | 383.00 | 485.72 | 615.08 |
| (11) St. Mary | 633.56 | | | | | | 604.52 | 209.12 | 522.68 |
| (12) Portland | 933.60 | | | | | | | 682.80 | 275.36 |
| (13) St. Thomas | 672.24 | | | | | | | | 743.52 |

Note: Shading indicates the possibility was not considered.
Source: Norconsult (1996).

To simplify the model, we only consider Norconsult's (1996) short list of nine possible landfill locations from an original candidate list of fifteen sites that could serve the thirteen Parish wastesheds. In addition, rather than looking at all possible combinations of Parishes and disposal sites, several were eliminated a-priori following Norconsult (1996) because the transport costs involved made them obviously infeasible. As Table 3 shows, we do allow the possibility of building a "super site" in any of the nine locations by permitting waste from the St. Andrew/Kingston metro area, which produces more than one third of the island's total waste, to be shipped to any of the nine possible disposal locations. However, for simplification, other shipment-disposal pairs involving transport over 200 round trip miles were eliminated, so not all of the rest of the possible 117 wasteshed/disposal site combinations are represented in the model.

Over long distances, waste can be hauled less expensively by a large tandem trailer than it can by the smaller trucks that are used for local collection. Therefore, minimum transport costs were obtained by including transfer stations in the haulage cost calculations.[10]

The transfer station calculation is simple. It involves solving for the distance from the centroid of the generation/collection point where a combination of local truck haulage to the transfer station and semitrailer haulage from the transfer station to the ultimate disposal site becomes cheaper than a direct

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[10] The calculations were performed outside of the model itself, to reduce model complexity for presentation purposes. In a real application, the engineering economics of transfer station alternatives could be embodied in the activity matrix of the programming model as mixed integer alternatives.

haul to the landfill using a smaller local collection truck.

Transport cost functions for direct haul using a 7 ton capacity flat bed tipper and for a transfer station and a 15 ton capacity semitrailer are co of an annualized capital cost per ton plus an operating cost per ton per kilometer of haul, using information in Norconsult (1996)[11]. The equations are plotted in Figure 3, which shows the minimum cost envelope formed from the two cost line segments associated with a transfer station located 65 kilometers from the generation point. Purely for demonstration purposes, it is assumed that the transfer station option would be technically feasible in all cases.

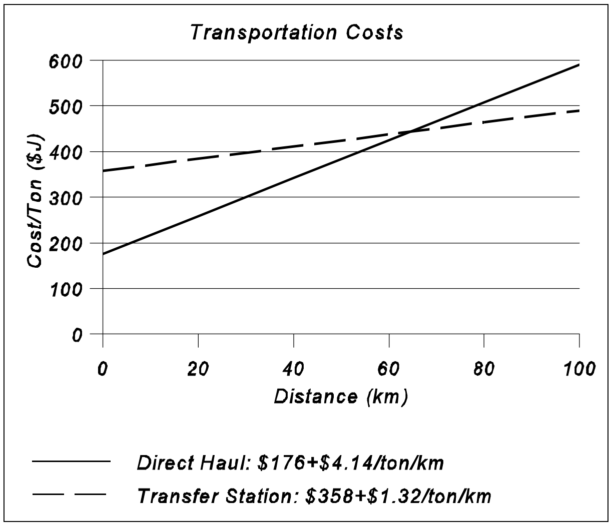

**Figure 3**. **Minimum Transportation Cost**

### Disposal Site Investment and Operating Costs

The landfilling options are intended to replace the existing dumps on the island with sanitary landfills. The costs for all investments reflect a useful design life of 20 years, a natural soil liner of 0.5 m thickness and a permeability of less than $10^{-7}$ centimeters per second. The associated site infrastructure is assummed to be identical for all sites and includes fencing, guardhouse, gates, weigh-bridge, all-weather paved access road, leachate collection, treatment and disposal system, surface runoff collection and drainage system, gas collection and flaring system, laboratory, storage , administration and staff buildings, compactor and bulldozer[12]. Investment and operating costs for landfills at four capacity levels appear in Table 4.

The total costs over the standard facility lifetime of 20 years have been annualized using the capital recovery factor[13]. Both the capital and operating costs increase less than proportionally with an increase in capacity (a 100 percent increase in capacity requires approximately a 62 percent increase in investment cost and a 69 percent increase in operating cost), consistent with the presence of scale economies.[14]

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[11] For example, the capital cost of a flat bed tipper truck is JA$ 2,500,000. Assuming a useful vehicle lifetime of 10 years, and zero salvage value, a second truck will have to be purchased mid-way through the 20 year project period whose present value is $805,000 (i.e. $\$2,500,000/[1+0.12]^{10}$). The annualized equivalent of the total vehicle cost is therefore $442,466 (i.e the c.r.f. of 0.13388 times the sum 2,500,000+805,000). Assuming one trip per day over 360 days and 7 tons hauled per trip the annualized cost is thus $176 per ton.

[12] More realistically, investment and operating costs could be allowed to differ according to the geographic, soil, and environmental characteristics of each site.

[13] The capital recovery factor applied to a present sum P produces the future series of uniform end-of-period payments R that will just recover the present sum over *n* periods with compound interest *i*. Symbolically, $R = P[(I(1+i)^n)/((1+i)^n-1)]$.

[14] The relationship between capital cost, C, and size, S, in general is $C=aS^{ß}$ (see Chase 1970). Regressions of the natural logarithms of investment cost and operating cost from the table against the logarithm of tons per day of capacity produced respective ß estimates of 0.62 (*t=6.2)* and 0.69 (*t=8.90)*. The fits were very tight, with respective $R^2$s of 0.95 and 0.98.

**Table 4. Annual Investment and Operating Cost by Landfill Size (i)** ***(1996 Jamaican Dollars)***

| Size (I) | 100 Tons per Day | 200 Tons per Day | 500 Tons per Day | 850 Tons per Day |
|---|---|---|---|---|
| Total Investment Cost | 170089000 | 191033000 | 428831000 | 588060000 |
| Annual Investment Cost [1] | 22771308 | 25575198 | 57411425 | 78728702 |
| Operating Cost, 20 Years | 27867160 | 35527950 | 81856770 | 112147200 |
| Annual Op. Cost per Ton [2] | 104 | 66 | 61 | 49 |

Notes: 1. Annualized by application of a capital recovery factor of 0.1338778 (20 years, 12% interest).
2. Annualized by application of a capital recovery factor of 0.1338778, and divided by tons/day times 360 days operation per year.

Source: Norconsult 1996.

### Optimal Results

The optimal integer programming solution involves investment in four sites from a possible nine, for an annual total cost of JA$358.7 million[15]. This result is exactly the same as the answer produced by Norconsult's brute force simulation.

The benefits of taking a region-wide approach to the siting problem are considerable, since if a site were to be built in each of the nine possible jurisdictions rather than optimizing over the country as a whole the total cost of the system would be 23 percent greater (JA$439.8 million). Over the life of the program a failure to take a regional perspective would lead to unnecessary extra costs of JA$606 million in present value terms, which amounts to roughly $16 million U.S. dollars.

The optimal solution involves one large 850 ton per day site (TPD) in St. Andrew, and three medium sized sites that can accommodate 200 tons per day in the Parishes of Manchester, St. James and St. Mary (Table 5). As might be expected, to minimize haulage costs, these sites are all close to the major poles of urban concentration in the southeast, south-central, northwest and northeast areas of the country (Kingston, Mandeville, Montego Bay, and Port Maria).

Due to the discrete nature of the capacity alternatives, one site, Manchester, only operates at 57 percent of full capacity because it cannot accommodate over 41,000 tons of waste per year with the smallest facility size (100 TPD, 36000 TPY) and therefore the next largest size, 200 TPD, must be built. The remaining three sites operate at or close to full design capacity. To achieve this, waste from Westmoreland and St. Andrew must be routed to more than one site.

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[15] The operations research software package ORSYS was used for this exercise. Other programs, such as LINDO, could also solve the optimization problem.

**Table 5. Optimal Site Investment and Waste Allocation: Financial Cost Minimization** *(tons per year)*

| **To Site:**<br>**From Parish** | **Site #3: Manchester 200 TPD** | **Site #5: St. James 200 TPD** | **Site # 8: St. Mary 200 TPD** | **Site #1: St. Andrew/KMA 850 TPD** |
|---|---|---|---|---|
| #3. Clarendon | 24184 | | | |
| #4. Manchester | 31025 | | | |
| #5. St. Elizabeth | 16790 | | | |
| Total Tons/Yr. (% Cap).: | 41006 (57%) | | | |
| #6. Westmoreland | | 5935 | | |
| #7. Hanover | | 12045 | | |
| #8. St. James | | 38690 | | |
| #9. Trelawny | | 15330 | | |
| Total Tons/Yr. (% Cap).: | | 72000 (100%) | | |
| #1. St. Andrew/KMA | | | 4425 | |
| #10. St. Ann | | | 31755 | |
| #11. St. Mary | | | 23360 | |
| #12. Portland | | | 9125 | |
| Total Tons/Yr. (% Cap).: | | | 68665 (95.4%) | |
| #1. St. Andrew/KMA | | | | 181725 |
| #2. St. Catherine | | | | 74825 |
| #3. Clarendon | | | | 15235 |
| #6. Westmoreland | | | | 19250 |
| #13. St. Thomas | | | | 14965 |
| Total Tons/Yr. (% Cap).: | | | | 306,000 (100%) |

# Public Choice and Environmental Considerations

## The Politics of Location Choice

By their very nature, landfill proposals attract opposition. While many potential problems can be reduced by proper design and management, landfills (or incinerator/landfill combinations) nevertheless may impose hidden costs on surrounding communities, which can become significant in the absence of professional waste management practices. Groundwater pollution is a major concern. Biological decomposition and chemical reactions in deposited waste produce a very strong wastewater (leachate) containing pollutants that, if allowed to seep into the ground, may contaminate aquifers. Methane and carbon dioxide gases formed by microbial reactions in the landfill can, if not controlled, lead to fires, explosions, and damage to vegetation planted to control landfill erosion. Traffic noise and traffic congestion are also potential negative factors. Finally, poor landfill operation can impose health, aesthetic, noise and air pollution damages as well if litter, pests, vermin, scavenging, fires and odors are not strictly controlled.(O'Leary and Walsh 1994; Corbitt 1989).

Ultimately, because of the negative externality problem, the choice of solid waste disposal facility location and technology must be made in the political arena (Lake 1989). Locational conflict cannot be avoided by imposing a false separation between facility planning and the facility location decision process, since once the spatial decisions are made known, controversy is likely to ensue. While developers may prefer to keep the site search process behind closed doors for as long as possible out of fear of public opposition and possible speculation in land, a policy of "decide-announce-defend" that postpones public participation for as long as possible may in fact maximize opposition to sites that have been selected on purely technical and financial criteria (O'Leary and Walsh 1994). As Lake (1989) observes "*To opt for efficiency over equity by selecting the lower-cost alternative (*i.e. choosing the less-affluent community) *is a political decision that should be made publicly and explicitly in the context of the facility planning process*"(p. xix). Moreover, a failure to involve the potentially affected population early-on is inconsistent with IDB environmental policies and procedures, and ignoring this fact could lead to a costly prolongation of the project preparation and approval period.

Locational conflict is "...a statement that the public differs in its political and value positions from those implicit in the siting decision" (Lake 1989, p. xviii). Anticipating and incorporating public preferences into the economic analysis may reduce the likelihood of reaching an unresolvable impasse over a landfill or incinerator location choice. This means that the minimization of regional investment and operating costs is insufficient; a more adequate analysis would minimize the sum of those two cost categories *plus* the sum of environmental damage mitigation costs and residual uncontrolled damages (Vaughan and Ardila 1993).

Because economic efficiency analysis does not directly address or resolve equity issues, the results of an empirical economic least cost analysis would best be used to *inform* the decision making process, not determine it. That in turn implies that the "economic justification" required for Bank lending should be interpreted in that spirit. In many cases the configuration of investments proposed for financing may differ from the "optimal" configuration prescribed by an economic model because of the workings of the public participation process, whose vagaries can only be imperfectly captured by the analyst. What an economic analysis can do for the decision maker, using the site specific contingent valuation approach outlined below, is pinpoint locations that are likely to be unpopular, and show the added cost implications of deviations from the efficient solution that are made to accommodate some of the concerns raised in the public consultation process.

## Introducing Differentiated Site Attributes and Environmental Damages

In order to simplify the exposition of the modeling approach, to this juncture, we have treated all sites as if they were the same except for their geographical location and size. Of course they are unlikely to be alike in all respects, and most engineering feasibility analyses try in some way (site selection screening, mitigation measures) to handle varying site characteristics.

Ideally, any landfill site  should have not only good accessibility, but also be relatively isolated so that odors and smoke do not bother nearby residents, be impermeable to avoid contamination of surface and groundwater supplies, and be well drained so that the waste material stays put during heavy rains. However, even with mitigating measures in place, there may be differential social costs to alternative disposal locations. Opaluch et. al. (1993) explain that there are tradeoffs involving the type of land use lost to a landfill (woodlands, wetlands, farm land), the landfill's perceived impact on public safety if the location is near schools or densely populated residential areas, and regional public good effects on wildlife habitat, air, and water quality that may not be entirely controllable.

One answer to the siting dilemma recommended by some economists (Mitchell and Carson 1986) is a decentralized market-like approach whereby communities would bid via an auction for the privilege of having a landfill, and the compensation payment they would require to accept it in their jurisdiction.. On the face of it, this proposal sounds good--clean, neat, and politically correct, with no modeling required. However, the suggestion has not found favor with public policy makers, who prefer a more centralized approach which identifies the preferred site or set of sites first using technical criteria, and then compensation, if necessary, is negotiated separately with communities near the best sites.

Opaluch et. al. (1993) identify three reasons why policy makers oppose auction mechanisms. First, compensation-based siting is regarded by the public at large as inequitable because poorer communities are more likely to be the low bidders. Second, the auction does not fully internalize social costs. Third, decision makers fear unreasonable or almost infinite compensation demands (which, of course, is inconsistent with the first objection). Finally, we might add that it is unlikely that a pure auction would minimize the landfill system costs over a large region, since it is not in the parochial interest of any of the participating communities to take a global minimization perspective.

Because of the impracticality of a completely decentralized approach, Opaluch et. al. (1993) propose a centralized decision site selection process based on technical criteria, as explained in the previous chapter, coupled with a decentralized ranking of potential sites based on their attributes and impacts. Rather than using actual referenda or auctions, Opaluch et. al. (1993), Swallow et. al. (1992, 1994) suggest constructing preference rankings for a list of sites based on community preferences revealed through hypothetical market surveys. In fact, monetary estimates of the relative disutility of alternative disposal locations can be extracted and incorporated directly into the MIP (see Appendices 2 and 3). Two routes to incorporating the monetary equivalent of the environmental and other disamenities imposed by landfills in the regional programming model **S** contingent valuation and hedonic analysis **S** are sketched below.

### Contingent Valuation

There are at least two variants of the contingent valuation approach valuing the damages associated with landfills. Both involve paired comparisons, but differ in the way the reference alternative is defined. The more conventional, and familiar, route involves asking a sample of respondents *in each jurisdiction* how much they would be willing to pay to avoid having a landfill with specified characteristics located in or near their community. Respondents can either be asked to directly reveal their desired payment amount (Roberts et. al. 1993) or they can be confronted with a pre-specified payment and asked a 'take it or leave it" referendum question (see Appendix 2). In either case, a separate exercise would have to be conducted at each of the potential landfill locations on the short list.

Swallow et. al. (1992, 1993) propose a paired comparison approach where respondents have to choose between two hypothetical landfills whose characteristics and costs differ, rather than choosing between having a landfill in the community or not. They argue that posing the question in this way is less threatening and divisive, and has a cost advantage since rather than sampling at each proposed site smaller random samples can be taken over the population. Repeated variation of the attributes and costs of the paired choices over the sample of respondents produces data for statistical estimation of a discrete choice random utility model. The statistical model recovers estimates of the parameters of the indirect utility function from which scoring indices, probability of site acceptance, and monetary measures of relative site disutility can be derived. The latter can be connected to the cost of investment choices in the MIP model.

Very briefly, and without proof (details are in Appendix 2) the paired comparison setup (Opaluch et. al. 1993) presents each individual in the survey sample with a choice between two hypothetical landfills that differ with respect to their location and neighborhood attributes, $\mathbf{Z_i}$, and their hypothetical fees, $\mathbf{F_i}$. The subscript (I=1,2) indexes the two choices. The location attributes include natural resources on the sites ( marsh, farm and woodland and pond acreage) that would be sacrificed to the landfills, quality of wildlife habitat (unique or normal) and groundwater quality. The neighborhood attributes within four square miles of the site include density of homes, existence of parkland and farms nearby, and highway access. The respondent with a given income, **Y**, will prefer $\text{Choice}_1$ to $\text{Choice}_2$ if it provides a higher utility level **V(Z,Y-F)**:

$$(5) \qquad \mathbf{V(Z_1, Y - F_1) > V(Z_2, Y - F_2)}$$

Once the survey data is in hand , a Logit probability of choice model can be estimated as a function of the utilities. Assuming a first order linear approximation for **V(C)**[16] the parameter vector(**a, ß, ?)** of the probability model can be estimated. The probability of making $\text{Choice}_1$, $\mathbf{P_1}$ depends on the attributes and costs of the choices:

$$(6) \quad \mathbf{P_1} = \frac{1}{[1 + \exp(\{\mathbf{a_1+\text{ß}_ZZ_1+?(Y-F_1)}\}-\{\mathbf{a_2+\text{ß}_ZZ_2+?(Y-F_2)}\})]}$$

where the intercepts a are allowed to differ between choices to capture generic differences not measured by the attributes, the z=1...Z dimensional vector of ßs apply to the characteristics, and ? is the (assumed constant) marginal utility of income. Simplifying the denominator of Eq. 6 above shows that income drops out as an argument in the "no income effects" version of the probability model:

$$(7) \quad \mathbf{P_1} = \frac{1}{[1 + \exp((\mathbf{a_1-a_2)+\text{ß}_Z(Z_1-Z_2)+?(F_2-F_1)})]}$$

Each option has a utility index $\mathbf{I_i}$ that can be measured up to an unknown scalar by evaluating the terms in brackets {} in Eq. 6 above. Swallow et. al. (1993) recommend using this measure as a way to rank sites. The scores can be transformed into Hicksian measures of monetary gain/loss for each site by dividing each by the estimate of the marginal

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[16] This results in the "no income effects" random utility model which imposes the restriction that the marginal utility of income is constant (see Appendix 2). Of course, a more flexible formulation would include socioeconomic variables and test the "no income effects" restriction (Ardila 1993, Swallow et. al. 1994). For ease of presentation, we abstract from these econometric wrinkles, which should be explored in any real application..

utility of income, ?.[17] Since a multiple choice logit model can be regarded as a series of pairwise models the probability estimates for more than two choices can be extended as a logistic function of all the site scores.

## Hedonic Analysis

Policy makers may be leery of allowing large willingness to pay surveys asking about landfill disamenities to be undertaken while the technical design process is ongoing. If that is the case, hedonic estimates of local (but not total) landfill damages might be obtainable by relating property values to the characteristics of the land, the residence, and the neighborhood (including the distance from the nearest landfill) via regression analysis. While this method has been successfully applied to landfills (Clark and Nieves 1994, Hite, 1995, Nelson et. al. 1992) it has several shortcomings relative to the contingent valuation approach.[18]

First, and perhaps foremost, there is no guarantee that increasing proximity to a landfill will be significantly related to decreased property values in an econometric hedonic exercise; in which case the cost of data acquisition and analysis would be without reward. Real world data sometimes holds nasty surprises. For instance, Schultze et. al. (1986) found that homes located closer to a major dump in Los Angeles had higher property values -- exactly the opposite of what one would expect. They explain this counterintuitive result by the presumed confounding effect of distance from the center city.

Second, the usual variable used to represent landfill disamenity in hedonic models is distance from the site. That implies that in aggregate predicted damages for each site will only vary across alternative sites if the value of surrounding property varies across alternative locations or if the number of households in the affected zone varies. The obvious implication of this damage metric is that poor or less densely populated areas suffer lower damages, and are more likely to be targets for landfills. Of course, if there is no significant variation across alternative landfill locations the optimal choice set will be unaffected-- social costs will just exceed financial costs by a constant offset.

Other problems with hedonics are whether the property value models realistically reflect prices that would obtain if households had full information, and whether they can be specified and estimated to produce a Hicksian welfare measure or just some approximation thereto that is not much more than a "damage avoided" estimate (Michaels and Smith 1988, Roberts et. al. 1991, Vaughan 1987b). These problems may be overcome, perhaps (see Hite 1995), but not, as is often assumed, with necessarily less time and effort than would be involved in contingent valuation.

In the next chapter a virtual reality version of the contingent valuation method is applied to the case study example, using the parameters of the Logit model estimated from Rhode Island survey data by Swallow et. al. (1992). A damage transfer is required because no data are available on site characteristics or public preferences in the Jamaica case.

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[17] The monetary values of the (dis)utility indices for each landfill location and size are computed in Appendix 3 using hypothetical, randomly generated attribute levels, **Z** which vary across sites. The parameter vector (a, ß, ?) that appears in the appendix table column labeled "Attribute Coefficient" is the same for all sites; where intercept (a) difference terms have been set to zero. Note that since annual investment and operating costs are included directly in the objective function of the MIP model, the index appearing in the Attribute Score column of the tables in Appendix 3 was evaluated with the attribute level of cost set to zero.

[18] It is possible to cast contingent valuation information in the hedonic framework by asking respondents to choose between two homes with identical features that vary only in the hypothetical purchase price and distance from the noxious facility (Smith and Desvousges 1986).

# The Case Study Revisited: Incorporating Environmental Costs

## Expanded MIP Model Specification

In the absence of contingent valuation information for the case study, hypothetical values have to be constructed to illustrate the effect of incorporating environmental damage costs into the objective function of MIP model. These costs are purely fictitious; they do not represent the preferences of the Jamaican population or the real attributes of the nine landfills at issue.

To generate the pseudo-damage estimates, the parameters of the "no income effects" (dis)utility function estimated by Swallow et. al. (1992)[19] were applied to randomly generated site attributes reported in Appendix 3. The total acreage of each alternative landfill size was calculated[20] and proportioned randomly between the land use types that are arguments in the (dis)utility function. Out-of-pocket investment and operating costs were not included in the utility indices because they are already captured in the MIP model.

Appendix 2 explains that utility index measures from random utility models (RUM) are only calculable relative to some reference level. Several choices of reference level are possible (the average site, the worst site in the set of nine, the worst possible site imaginable, any one of the nine sites), since only the *difference* in environmental damage costs among alternatives will influence the optimal solution. We arbitrarily chose to put financial costs for investment and operation on an equal absolute footing with environmental damages by evaluating environmental damages relative to the best possible situation of a fictitious landfill that imposes zero disutility and has environmental damage of zero[21].

To convert the environmental damage (dis)utility scores of the sites in the model into a money measure, the marginal utility of Jamaican household income estimated by IDB/OEO (1992) was used instead of the Rhode Island estimate from Swallow et. al. (1992, 1993). The Jamaica estimate of the marginal utility of income obtained by IDB/OEO (0.01322 per household of four persons) makes the average value of per capita environmental damages in our Jamaica application, $11 U.S. equivalent in 1996 for a 500 tpd site, which is 5% of what it would have been had the Rhode Island coefficient (0.0029 per person) been used. This percentage difference is in line with the relative per capita income levels in the two countries, (in 1992 U.S dollars, $1,323 for Jamaica and $23,822 for the U.S.) so the magnitude of the Jamaica damages produced by the transfer of the Swallow et. al. model is not unreasonable. The hypothetical per household damage estimates for each site and capacity appear in Table 6.

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[19] These functions are convenient for transfer to our case because they do not include socioeconomic characteristics of the respondents. In any actual application, damages by socioeconomic group should probably be estimated (Swallow et. al. 1994).

[20] Following Dooley et. al. (1993):

ACRES OF FILL AREA
= {20 yr.*[(TPD*2200 lb/MT)/800 lb.compacted density/yd.$^3$]*360 days/yr.*27 ft.$^3$/yd.$^3$}
÷ (20 ft. depth*43560 ft.$^2$/acre).

A border of 500 ft. around the FILL AREA was assumed. to get the total acreage. With these assumptions, total area is approximately equal to TPD. Swallow et. al's experiment was scaled to a 400 acre site.

[21] The environmental cost difference between the disposal activity selected to represent the reference level of damage and the other disposal activity options evaluated in the objective function is invariant to the choice of reference activity. The reference activity choice merely implies the subtraction of some constant monetary amount from the objective function entry for each and every disposal option, where the magnitude of that constant is defined by which activity is assigned to serve as the reference activity.

| Table 6. Per Household Environmental Costs (1996 JA$) | | | | |
|---|---|---|---|---|
| SITE | 100 TPD | 200 TPD | 500 TPD | 850 TPD |
| 1. St. Andrew/KMA | 1,080 | 1,106 | 1,183 | 1,282 |
| 2. Clarendon | 459 | 496 | 645 | 888 |
| 3. Manchester | 1,513 | 1,747 | 2,632 | 4,024 |
| 4. Westmoreland | 892 | 1,109 | 1,818 | 2,802 |
| 5. St. James | 1,323 | 1,569 | 2,455 | 3,790 |
| 6. Trelawny | 1,059 | 1,535 | 3,408 | 6,428 |
| 7. St. Ann | 387 | 390 | 398 | 407 |
| 8. St. Mary | 1,276 | 1,421 | 1,965 | 2,810 |
| 9. Portland | 1,457 | 1,682 | 2,376 | 3,283 |

Source: Adapted from Swallow et. al. (1992) and Opaluch et. al. (1993) using a marginal utility of income estimate of 0.01322 from IDB/OEO 1992. Monetary values were obtained by dividing the utility index scores reported in the last row of the tables in Appendix 3 by ?= 0.01322 and updating them from 1992 to 1996 dollars using an inflation factor of 4.43 based on the Jamaica CPI from *International Financial Statistics*.

Per household damages do not ascend linearly with site size in Table 6 because of the existence of interaction terms between marsh and pond acreage in the Swallow et. al. damage functions. A location like Trelawny, for example, happens to have randomly drawn a substantial portion of non-fill area in marsh and pond, so damages increase non-linearly with capacity, while a location like St. Andrew has very little marsh and pond area, making damages relatively invariant over site size (see Appendix 3 for details). Total damages appear in Table 7.

| Table 7. Aggregate Disutility (1996 JA$) | | | | | |
|---|---|---|---|---|---|
| SITE | 100 TPD | 200 TPD | 500 TPD | 850 TPD | Households |
| 1. St. Andrew/KMA | 190,825,194 | 195,420,170 | 209,173,128 | 226,559,568 | 176,750 |
| 2. Clarendon | 25,673,981 | 27,749,851 | 36,084,333 | 49,702,037 | 55,975 |
| 3. Manchester | 66,736,817 | 77,032,500 | 116,090,535 | 177,440,261 | 44,100 |
| 4. Westmoreland | 29,361,074 | 36,499,005 | 59,852,325 | 92,264,874 | 32,925 |
| 5. St. James | 55,784,556 | 66,184,855 | 103,551,444 | 159,851,146 | 42,175 |
| 6. Trelawny | 19,699,653 | 28,547,510 | 63,385,148 | 119,563,610 | 18,600 |
| 7. St. Ann | 15,078,772 | 15,192,643 | 15,496,803 | 15,828,072 | 38,925 |
| 8. St. Mary | 36,564,950 | 40,724,707 | 56,290,610 | 80,494,450 | 28,650 |
| 9. Portland | 28,732,974 | 33,176,660 | 46,871,020 | 64,756,000 | 19,725 |

Note: Number of households (Parish population divided by 4) times per household damage from preceding table.

Aggregating up the per household damages raises a critical question--should all households in a jurisdiction be considered as being equally harmed or only households within a given distance from each site? Parishes in Jamaica are small; in general the greatest distance from the center of any Parish to its most distant border is less than 20 miles. Smith (1986) and Mitchell and Carson (1986) find that at this short distance more than three quarters of the population would oppose a waste facility, so we apply damages to the entire population of each Parish where a landfill could be located in Table 7.[22] The sensitivity of the model to this assumption is explored below, after the optimal results are presented.

In sum, the structure of the model given in Eqs. (1) through (4) above remains unaltered, but the objective function is augmented to include lump sum environmental damage costs:

$$\begin{aligned}\min_{IS_{ij},GS_{kji},VS_{ij}} \quad C \;\; ' \;\; & \mathbf{j}_i \, \mathbf{j}_j \;\; FC_{ij}IS_{ij} \\ \% \; & \mathbf{j}_i \, \mathbf{j}_j \;\; EC_{ij}IS_{ij} \\ \% \; & \mathbf{j}_i \, \mathbf{j}_j \;\; VC_{ij}VS_{ij} \\ \% \; & \mathbf{j}_i \, \mathbf{j}_k \, \mathbf{j}_j \;\; TC_{kji}GS_{kji}\end{aligned}$$

where $EC_{ij}$ represents total annual environmental damages from Table 7.

Rather than calculating lump sum environmental damages exogenously, a more sophisticated (and realistic) approach would be to explicitly include detailed damage generation and mitigation activities in the model (see Russell and Vaughan 1976) along with remaining uncontrolled damage costs by type from the contingent choice functions. This more detailed model would be able to find the landfill locations, scales *and designs* that minimize the sum of annualized investment costs, operation costs, mitigation costs, and residual damages. Lack of sufficient information prevented the demonstration of this refinement here.

## Optimal Results

As we calculated them, environmental damages bulk large in total disposal cost, being about as large as financial costs in the original solution that ignores them in minimization. The total environmental cost attributable to the four sites (Manchester, St. James, St. Mary and St. Andrew) that minimize out-of-pocket cost only (see Table 5 above) is JA$ 410 million per year, so the total financial and environmental cost of that previously optimal configuration is the sum of annual resource costs of JA$ 359 million and environmental damages, or JA$ 769 million. Permitting the MIP model to search over all alternatives to find a new optimum that minimizes financial *and* environmental costs (see Table 8) leads to higher investment, transport and operating costs (JA$ 459 million per year), but lower environmental costs (JA$ 150 million) and hence lower total system costs overall (JA$ 609 million). In the new optimum that minimizes total social cost, environmental costs comprise one fourth of the total, while they would have amounted to half of a higher total had we stuck with the original optimum that ignores non-market costs.

The lesson is that from society's viewpoint the purely technical solution, while it may seem cheaper in terms of actual construction and operation outlays, is inferior. On net, it would be more socially costly than the financial and environmental damage optimum by JA$ 160 per year (over 4 million US$ annually, or more than 30 million US$ in present value terms over the life of the project). In short, ignoring public preferences in landfill siting when environmental damages are significant could easily lead to socially inefficient decisions.

Table 8 demonstrates that a radical reshuffling of sites and site sizes is involved in the new optimum. None of the previously preferred locations remain viable when environmental damages are factored in. Instead of three sites of 200 tpd and one of 850, the five sites in the new optimum involve two small 100 tpd facilities in Trelawny and Portland, two 200 tpd locations in Westmoreland and St. Ann, and, as before, one large 850 tpd landfill, in Clarendon

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[22] In a real application, serious attention should be given to this issue in both the design of the contingent valuation survey instrument and the calculation of aggregate damages. Swallow et. al. (1992, 1993) do not include a distance variable in their damage specification.

**Table 8. Optimal Site Investment and Waste Allocation: Financial Plus Environmental Cost Minimization**
*(tons per year)*

| To Site: | Site #2: Clarendon 850 TPD | Site #4: Westmoreland 200 TPD | Site #6: Trelawny 100 TPD | Site #7: St. Ann 200 TPD | Site #9 Portland 100 TPD |
|---|---|---|---|---|---|
| From Parish | | | | | |
| #1. St. Andrew/KMA | 143940 | | | | |
| #2. St. Catherine | 74825 | | | | |
| #3. Clarendon | 39420 | | | | |
| #4. Manchester | 31025 | | | | |
| #5. St. Elizabeth | 16790 | | | | |
| Total Tons/Yr. (% Cap).: | 306000 (100%) | | | | |
| #6. Westmoreland | | 13415 | | | |
| #7. Hanover | | 12045 | | | |
| #8. St. James | | 18020 | | | |
| #1. St. Andrew/KMA | | 13415 | | | |
| Total Tons/Yr. (% Cap).: | | 68665 (95%) | | | |
| #8. St. James | | | 20670 | | |
| #9.Trelawny | | | 15330 | | |
| Total Tons/Yr. (% Cap).: | | | 36000(100%) | | |
| #1. St. Andrew/KMA | | | | 28795 | |
| #10. St. Ann | | | | 31755 | |
| #11. St. Mary | | | | 11450 | |
| Total Tons/Yr. (% Cap).: | | | | 72000 (100%) | |
| #11. St. Mary | | | | | 11910 |
| #12. Portland | | | | | 9125 |
| #13. St. Thomas | | | | | 14965 |
| Total Tons/Yr. (% Cap).: | | | | | 36000 (100%) |

(instead of St. Andrew), to handle the large amount of waste generated by St. Andrew/Kingston and St. Catherine. To adjust to a larger number of smaller sites, single origin-multiple destination routings appear for the generating Parishes of St. James and St. Andrew.

The reconfiguration of the optimum is due in part to the magnitude of per-household damages across sites and sizes and in part to the population in each Parish where a site potentially can be placed. Ironically, the biggest disposers are the greatest opposers. This is particularly obvious for the heavily populated St. Andrew/Kingston area, whose aggregate dollar-damage votes militate against the large Riverton-

Kingston landfill in favor of a landfill of equal size in the less heavily populated Parish of Clarendon.

### Sensitivity

As noted above, it is not clear whether all households would perceive the same level of disutility from a given landfill, no matter how far away from it they are. The sensitivity of the model to this assumption can be explored by parameterizing the magnitude of environmental costs relative to the benchmark level, which treats all citizens as equally affected, independent of distance.

Even if only 5% of the population were to perceive a negative effect from a landfill (i.e. environmental damages reduced by 95%), the optimal solution would not be the same as the optimum under purely financial cost minimization. The 200 TPD Manchester site would be dropped in favor of a site of the same capacity in Clarendon, raising total costs from JA$359 to JA$379 million, of which JA$18 million would be from environmental damages.

This solution holds until environmental costs rise to 40% of the original baseline, whereupon a 200 TPD landfill in Westmoreland becomes preferable to the one in St. James, still retaining the Clarendon location and sites in St. Mary and St. Andrew from the original financial cost minimization (Table 5). These are minor reevaluations, to be sure, as they involve only one location, but a real reconfiguration occurs if environmental costs are scaled to 50% of the full damage baseline. Then, the large 850 TPD landfill serving Kingston becomes unattractive, and is superceded by one of the same size in Clarendon. In addition, the 200 TPD St. James landfill comes back in, along with one in Portland. For environmental costs between 60 to 100% of the baseline, the configuration in Table 8 holds sway.

In sum, environmental damages do not have to be huge in order to induce some rethinking of what is optimal, and if they are non-trivial, major adjustments may be required.

# Concluding Observations

An integrated regional approach to the solid waste disposal problem can produce lower system-wide investment and operating costs than a piecemeal, "one-project-at-a-time" solution. In the case study a cost saving of almost 20% was achieved. The simple optimization modeling method of mixed integer programming can solve such regional site selection problems more quickly and accurately than brute force simulation of all possible alternatives, and is easier to update should cost estimates and site possibilities change during the course of project preparation. The minimization of social costs rather than just financial costs is easy to accommodate in the MIP framework. The dimension of environmental impact assessment, which is too often treated as a parallel, unconnected adjunct to project design, can be brought directly into the economic project analysis by including environmental damage estimates and mitigation activities in the model.

The simple model presented here abstracts from several dimensions of the broader solid waste management problem, which includes generation, recycling, reuse and ultimate disposal, and does not evaluate the desirability of incinerators rather than landfills.[23] Nevertheless, the MIP structure is flexible and allows the analyst to expand the model's scope and degree of detail to explicitly accommodate features that have either been ignored or treated as given initial conditions in our worked example.

For instance, the economic feasibility of waste minimization practices, such as recycling or composting, can be evaluated by comparing the cost savings they produce (i.e. through a reduction in the transportation, investment, and operating costs needed to dispose of a smaller total waste stream, $WASTE_k$ for all $k$ in Eq. [1] above) to the annual costs of establishing those types of programs.

Another refinement that would make the model more realistic would be to permit staged retirement of existing landfills over time as their capacity becomes exhausted, replacing them as necessary, rather than in a greenfield analysis that replaces all existing capacity immediately with new, environmentally safe facilities.. One way to represent this problem in the MIP model would be to divide the entire planning period into separate sub-periods, allowing existing landfill capacity constraints to be relaxed by the purchase of new capacity at new sites as waste volume grows over time (Manne 1967, Cohen and Cyert 1975, Ch. 16).[24]

Finally, instead of specifying a standard set of environmental mitigation activities and costs for all landfill locations, residuals generation and environmental mitigation activities could be explicitly represented in the activity matrix. This would permit a closer examination of the marginal costs of increasingly stringent environmental standards, and perhaps even a comparison of promulgated standards with the optimal degree of environmental protection obtainable through an equilization of the marginal costs of mitigation with the marginal environmental damages avoided.

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[23] The behavioral responses of waste generating firms or households to collection or tipping fees or recycling incentives are not modeled. Neither are optimal within-city collection routes considered. Financial and public/private service provision issues are not addressed because the core issue here is the optimal technical design of the investment components in the disposal part of the system, not how they are financed, administered and run, once designed.

[24] In our setup, useful landfill lifetimes are exogenously specified. A much more complicated decision to model involves choosing the rate of filling, inclusive of waste minimization options, that optimes the useful life of a landfill of a given size. The solution of this variable lifetime problem requires a dynamic model built using the principles of optimal resource depletion theory. See Lund (1990a,b), Jacobs and Everett (1990), Everett, Mondak and Jacobs (1993), and Ready and Ready (1995).

# Appendix 1.Formula Listing for the Mixed Integer Model Example

OBJECTIVE: MINIMIZE COST
CONSTRAINTS: 94 VARIABLES: 264 SLACKS: 58
NONZEROS: 908 INTEGERS: 36 NONLINEAR: 0 DENSITY: 2.9071

## I. Objective Function

COST=
+22771307*(IS11+..+IS19)+25575198*(IS21+..+IS29)+57411424*(IS31+..+IS39)+78728701*(IS41+..+IS49)+103.6*(VS11+..+VS19)+66.1*(VS21+..+VS29)+60.9*(VS31+..+VS39)+49.1*(VS41+..+VS49)+184.28*GS111+504.2*GS121+636.2*GS131+900.2*GS141+960.9*GS151+871.16*GS161+715.4*GS171+633.56*GS181+794.6*GS191+291.92*GS211+491.96*GS221+570.2*GS231+504.2*GS311+291.92*GS321+477.8*GS331+636.2*GS411+456.68*GS421+225.68*GS431+725.96*GS511+549.08*GS521+548.6*GS531+929.2*GS611+333.32*GS641+654.64*GS651+1197.6*GS711+300.2*GS741+474.08*GS751+960.9*GS811+625.64*GS841+242.24*GS851+451.4*GS861+1010.16*GS911+465.8*GS951+233.96*GS961+715.4*GS1011+620.36* GS1051+383*GS1071+485.72*GS1081+615.08*GS1091+633.56*GS1111+604.52*GS1171+209.12*GS1181+522.68*GS1191+933.6*GS1211+682.8*GS1281+275.36*GS1291+672.24*GS1311+743.52*GS1391+184.28*GS112+504.2*GS122+636.2*GS132+900.2*GS142+960.9*GS152+871.16*GS162+715.4*GS172+633.56*GS182+794.6*GS192+291.92*GS212+491.96*GS222+570.2*GS232+504.2*GS312+291.92*GS322+477.8*GS332+636.2*GS412+456.68*GS422+225.68*GS432+725.96*GS512+549.08*GS522+548.6*GS532+929.2*GS612+333.32*GS642+654.64*GS652+1197.6*GS712+300.2*GS742+474.08*GS752+960.9*GS812+625.64*GS842+242.24*GS852+451.4*GS862+1010.16*GS912+465.8*GS952+233.96*GS962+715.4*GS1012+620.36*GS1052+383*GS1072+485.72*G1082+615.08*GS1092+633.56*GS1112+604.52*GS1172+209.12*GS1182+522.68*GS1192+933.6*GS1212+682.8*GS1282+275.36*GS1292+672.24*GS1312+743.52*GS1392+184.28*GS113+504.2*GS123+636.2*GS133+900.2*GS143+960.9*GS153+871.16*GS163+715.4*GS173+633.56*GS183+794.6*GS193+291.92*GS213+491.96*GS223+570.2*GS233+504.2*GS313+291.92*GS323+477.8*GS333+636.2*GS413+456.68*GS423+225.68*GS433+725.96*GS513+549.08*GS523+548.6*GS533+929.2*GS613+333.32*GS643+654.64*GS653+1197.6*GS713+300.2*GS743+474.08*GS753+960.9*GS813+625.64*GS843+242.24*GS853+451.4*GS863+1010.16*GS913+465.8*GS953+233.96*GS963+715.4*GS1013+620.36*GS1053+383*GS1073+485.72*GS1083+615.08*GS1093+633.56*GS1113+604.52*GS1173+209.12*GS1183+522.68*GS1193+933.6*GS1213+682.8*GS1283+275.36*GS1293+672.24*GS1313+743.52*GS1393+184.28*GS114+504.2*GS124+636.2*GS134+900.2*GS144+960.9*GS154+871.16*GS164+715.4*GS174+633.56*GS184+794.6*GS194+291.92*GS214+491.96*GS224+570.2*GS234+504.2*GS314+291.92*GS324+477.8*GS334+636.2*GS414+456.68*GS424+225.68*GS434+725.96*GS514+549.08*GS524+548.6*GS534+929.2*GS614+333.32*GS644+654.64*GS654+1197.6*GS714+300.2*GS744+474.08*GS754+960.9*GS814+625.64*GS844+242.24*GS854+451.4*GS864+1010.16*GS914+465.8*GS954+233.96*GS964+715.4*GS1014+620.36*GS1054+383*GS1074+485.72*GS1084+615.08*GS1094+633.56*GS1114+604.52*GS1174+209.12*GS1184+522.68*GS1194+933.6*GS1214+682.8*GS1284+275.36*GS1294+672.24*GS1314+743.52*GS1394

## II. Row Constraints

WASTE1 (GS111+..+GS191)+(GS112+..+GS192)+(GS113+..+GS193)+(GS114+..+GS194)>=186150
WASTE2 (GS211+..+GS231)+(GS212+..+GS232)+(GS213+..+GS233)+(GS214+..+GS234)>=74825
WASTE3 (GS311+..+GS331)+(GS312+..+GS332)+(GS313+..+GS333)+(GS314+..+GS334)>=39420
WASTE4 (GS411+..+GS431)+(GS412+..+GS432)+(GS413+..+GS433)+(GS414+..+GS434)>=31025
WASTE5 (GS511+..+GS531)+(GS512+..+GS532)+(GS513+..+GS533)+(GS514+..+GS534)>=16790
WASTE6 (GS611+..+GS651)+(GS612+..+GS652)+(GS613+..+GS653)+(GS614+..+GS654)>=25185
WASTE7 (GS711+..+GS751)+(GS712+..+GS752)+(GS713+..+GS753)+(GS714+..+GS754)>=12045
WASTE8 (GS811+..+GS861)+(GS812+..+GS862)+(GS813+..+GS863)+(GS814+..+GS864)>=38690
WASTE9 (GS911+..+GS961)+(GS912+..+GS962)+(GS913+..+GS963)+(GS914+..+GS964)>=15330
WASTE10 (GS1011+..+GS1091)+(GS1012+..+GS1092)+(GS1013+..+GS1093)+(GS1014+..+GS1094)>=31755
WASTE11 (GS1111+..+GS1191)+(GS1112+..+GS1192)+(GS1113+..+GS1193)+(GS1114+..+GS1194)>=23360
WASTE12 (GS1211+..+GS1291)+(GS1212+..+GS1292)+(GS1213+..+GS1293)+(GS1214+..+GS1294)>=9125
WASTE13 GS1311+GS1391+GS1312+GS1392+GS1313+GS1393+GS1314+GS1394>=14965

| | |
|---|---|
| TRANF1 | -VS11+GS111+GS211+GS311+GS411+GS511+GS611+GS711+GS811+GS911+GS1011+GS1111+GS1211+GS1311=0 |
| TRANF2 | -VS21+GS112+GS212+GS312+GS412+GS512+GS612+GS712+GS812+GS912+GS1012+GS1112+GS1212+GS1312=0 |
| TRANF3 | -VS31+GS113+GS213+GS313+GS413+GS513+GS613+GS713+GS813+GS913+GS1013+GS1113+GS1213+GS1313=0 |
| TRANF4 | -VS41+GS114+GS214+GS314+GS414+GS514+GS614+GS714+GS814+GS914+GS1014+GS1114+GS1214+GS1314=0 |
| TRANF5 | -VS12+GS121+GS221+GS321+GS421+GS521=0 |
| TRANF6 | -VS22+GS122+GS222+GS322+GS422+GS522=0 |
| TRANF7 | -VS32+GS123+GS223+GS323+GS423+GS523=0 |
| TRANF8 | -VS42+GS124+GS224+GS324+GS424+GS524=0 |
| TRANF9 | -VS13+GS131+GS231+GS331+GS431+GS531=0 |
| TRANF10 | -VS23+GS132+GS232+GS332+GS432+GS532=0 |
| TRANF11 | -VS33+GS133+GS233+GS333+GS433+GS533=0 |
| TRANF12 | -VS43+GS134+GS234+GS334+GS434+GS534=0 |
| TRANF13 | -VS14+GS141+GS641+GS741+GS841=0 |
| TRANF14 | -VS24+GS142+GS642+GS742+GS842=0 |
| TRANF15 | -VS34+GS143+GS643+GS743+GS843=0 |
| TRANF16 | -VS44+GS144+GS644+GS744+GS844=0 |
| TRANF17 | -VS15+GS151+GS651+GS751+GS851+GS951+GS1051=0 |
| TRANF18 | -VS25+GS152+GS652+GS752+GS852+GS952+GS1052=0 |
| TRANF19 | -VS35+GS153+GS653+GS753+GS853+GS953+GS1053=0 |
| TRANF20 | -VS45+GS154+GS654+GS754+GS854+GS954+GS1054=0 |
| TRANF21 | -VS16+GS161+GS861+GS961=0 |
| TRANF22 | -VS26+GS162+GS862+GS962=0 |
| TRANF23 | -VS36+GS163+GS863+GS963=0 |
| TRANF24 | -VS46+GS164+GS864+GS964=0 |
| TRANF25 | -VS17+GS171+GS1071+GS1171=0 |
| TRANF26 | -VS27+GS172+GS1072+GS1172=0 |
| TRANF27 | -VS37+GS173+GS1073+GS1173=0 |
| TRANF28 | -VS47+GS174+GS1074+GS1174=0 |
| TRANF29 | -VS18+GS181+GS1081+GS1181+GS1281=0 |
| TRANF30 | -VS28+GS182+G1082+GS1182+GS1282=0 |
| TRANF31 | -VS38+GS183+GS1083+GS1183+GS1283=0 |
| TRANF32 | -VS48+GS184+GS1084+GS1184+GS1284=0 |
| TRANF33 | -VS19+GS191+GS1091+GS1191+GS1291+GS1391=0 |
| TRANF34 | -VS29+GS192+GS1092+GS1192+GS1292+GS1392=0 |
| TRANF35 | -VS39+GS193+GS1093+GS1193+GS1293+GS1393=0 |
| TRANF36 | -VS49+GS194+GS1094+GS1194+GS1294+GS1394=0 |

| | | | |
|---|---|---|---|
| CAPAC11 | 36000*IS11-VS11>=0 | CAPAC12 | 36000*IS12-VS12>=0 |
| CAPAC13 | 36000*IS13-VS13>=0 | CAPAC14 | 36000*IS14-VS14>=0 |
| CAPAC15 | 36000*IS15-VS15>=0 | CAPAC16 | 36000*IS16-VS16>=0 |
| CAPAC17 | 36000*IS17-VS17>=0 | CAPAC18 | 36000*IS18-VS18>=0 |
| CAPAC19 | 36000*IS19-VS19>=0 | CAPAC21 | 72000*IS21-VS21>=0 |
| CAPAC22 | 72000*IS22-VS22>=0 | CAPAC23 | 72000*IS23-VS23>=0 |
| CAPAC24 | 72000*IS24-VS24>=0 | CAPAC25 | 72000*IS25-VS25>=0 |
| CAPAC26 | 72000*IS26-VS26>=0 | CAPAC27 | 72000*IS27-VS27>=0 |
| CAPAC28 | 72000*IS28-VS28>=0 | CAPAC29 | 72000*IS29-VS29>=0 |
| CAPAC31 | 180000*IS31-VS31>=0 | CAPAC32 | 180000*IS32-VS32>=0 |
| CAPAC33 | 180000*IS33-VS33>=0 | CAPAC34 | 180000*IS34-VS34>=0 |
| CAPAC35 | 180000*IS35-VS35>=0 | CAPAC36 | 180000*IS36-VS36>=0 |
| CAPAC37 | 180000*IS37-VS37>=0 | CAPAC38 | 180000*IS38-VS38>=0 |
| CAPAC39 | 180000*IS39-VS39>=0 | CAPAC41 | 306000*IS41-VS41>=0 |
| CAPAC42 | 306000*IS42-VS42>=0 | CAPAC43 | 306000*IS43-VS43>=0 |
| CAPAC44 | 306000*IS44-VS44>=0 | CAPAC45 | 306000*IS45-VS45>=0 |

| | | | |
|---|---|---|---|
| CAPAC46 | 306000*IS46-VS46>=0 | CAPAC47 | 306000*IS47-VS47>=0 |
| CAPAC48 | 306000*IS48-VS48>=0 | CAPAC49 | 306000*IS49-VS49>=0 |

| | | | |
|---|---|---|---|
| ISITE | IS11+IS21+IS31+IS41<=1 | ISITE2 | IS12+IS22+IS32+IS42<=1 |
| ISITE3 | IS13+IS23+IS33+IS43<=1 | ISITE4 | IS14+IS24+IS34+IS44<=1 |
| ISITE5 | IS15+IS25+IS35+IS45<=1 | ISITE6 | IS16+IS26+IS36+IS46<=1 |
| ISITE7 | IS17+IS27+IS37+IS47<=1 | ISITE8 | IS18+IS28+IS38+IS48<=1 |
| ISITE9 | IS19+IS29+IS39+IS49<=1 | | |

| | | | |
|---|---|---|---|
| BOUND | 1>=IS11 | BOUND | 1>=IS12 |
| BOUND | 1>=IS13 | BOUND | 1>=IS14 |
| BOUND | 1>=IS15 | BOUND | 1>=IS16 |
| BOUND | 1>=IS17 | BOUND | 1>=IS18 |
| BOUND | 1>=IS19 | BOUND | 1>=IS21 |
| BOUND | 1>=IS22 | BOUND | 1>=IS23 |
| BOUND | 1>=IS24 | BOUND | 1>=IS25 |
| BOUND | 1>=IS26 | BOUND | 1>=IS27 |
| BOUND | 1>=IS28 | BOUND | 1>=IS29 |
| BOUND | 1>=IS31 | BOUND | 1>=IS32 |
| BOUND | 1>=IS33 | BOUND | 1>=IS34 |
| BOUND | 1>=IS35 | BOUND | 1>=IS36 |
| BOUND | 1>=IS37 | BOUND | 1>=IS38 |
| BOUND | 1>=IS39 | BOUND | 1>=IS41 |
| BOUND | 1>=IS42 | BOUND | 1>=IS43 |
| BOUND | 1>=IS44 | BOUND | 1>=IS45 |
| BOUND | 1>=IS46 | BOUND | 1>=IS47 |
| BOUND | 1>=IS48 | BOUND | 1>=IS49 |

# Appendix 2. Theoretical Background on Valuation of Site Attributes.

## Utility-Theoretic Motivation

Following the development in Johansson et. al. (1989) and Hanemann (1984)[25] the indirect utility function of a household with income $\boldsymbol{y}$ consuming a private good (a Hicksian composite commodity with price normalized to 1) conditional on the quality of a public good $\boldsymbol{z}$ (say, a landfill) is:

(1) $\boldsymbol{V} = \boldsymbol{V}(\boldsymbol{z},\boldsymbol{y})$

The rational respondent knows the utility function with certainty but may make errors in maximization because of imperfect perception, and to the econometrician the indirect utility function contains unobservable stochastic components. So, adding an independent, identically distributed error term with 0 mean, e, to reflect randomness the utility model is:

(2) $\boldsymbol{v}(\boldsymbol{z},\boldsymbol{y}) + \mathrm{e} = \boldsymbol{V}(\boldsymbol{z},\boldsymbol{y})$

The deterministic part of the utility function is $\boldsymbol{v}(\boldsymbol{z},\boldsymbol{y})$, and because the expected value of the error term is zero, the researcher's expectations will be correct on average.

In the paired comparison survey[26], the respondent is offered a change in the quality of the public good from level $\boldsymbol{z}_1$ to level $\boldsymbol{z}_2$ provided the household sacrifices income in the form of a payment of $A$ per year. On average the respondent will select the option with less income (by an amount $-A$) and attribute bundle $\boldsymbol{z}_2$ (Choice$_2$) if it provides a level of utility that is is at least as high as the utility level of the Choice$_1$ option offering attribute bundle $\boldsymbol{z}_1$at the initial income level:[27]

(3) $\boldsymbol{v}(\boldsymbol{z}_2,\boldsymbol{y} - A) + \mathrm{e}_2 \geq \boldsymbol{v}(\boldsymbol{z}_1,\boldsymbol{y}) + \mathrm{e}_1$

Rearranging, the condition is equivalently:

(4) $\boldsymbol{v}(\boldsymbol{z}_2,\boldsymbol{y} - A) - \boldsymbol{v}(\boldsymbol{z}_1,\boldsymbol{y}) + \mathrm{e}_2 \geq \mathrm{e}_1$

Taking the total differential of the indirect utility function (the r.h.s. of Appendix Eq. 2 above) to linearly approximate the condition for preferring Choice$_2$ over Choice$_1$:

(5) $[\partial \boldsymbol{v}(\boldsymbol{z},\boldsymbol{y})/\partial \boldsymbol{z}]d\boldsymbol{z} + [\partial \boldsymbol{v}(\boldsymbol{z},\boldsymbol{y})/\partial \boldsymbol{y}]d\boldsymbol{y} + \mathrm{e}_2 \geq \mathrm{e}_1$

or, since $d\boldsymbol{y}$ equals $-A$, the linear approximation is:

(6) $[\partial \boldsymbol{v}(\boldsymbol{z},\boldsymbol{y})/\partial \boldsymbol{z}]d\boldsymbol{z} - [\partial \boldsymbol{v}(\boldsymbol{z},\boldsymbol{y})/\partial \boldsymbol{y}]A + \mathrm{e}_2 \geq \mathrm{e}_1$

In most surveys, the quality variable $\boldsymbol{z}$ has multidimensional attributes (site quality, for instance, depends on the existing land use mix at each site, the attributes of the surrounding neighborhood etc.). The respondent is faced with two states of nature for $\boldsymbol{z}$,which for convenience can be represented as a binary (0,1) on/off switch, so $d\boldsymbol{z}$ equals one. Then the

---

[25] See Ardila (1993) and McConnell (1990, 1995) for a more in-depth treatment of theory and estimation issues.

[26] Opaluch et. al.'s 1993 pairwise comparison presents the individual with a fee for each alternative. In this exposition, **A** equivalently represents the *difference* between the hypothetical fees (**F**) charged for Choice $_1$ and Choice $_2$ in the paired comparison referendum (i.e. $\mathbf{A}=\mathbf{F}_2 - \mathbf{F}_1$).

[27] Solely for explanatory purposes we assume $\boldsymbol{z}_2$ is superior to $\boldsymbol{z}_1$ and $\boldsymbol{A}$ involves a deduction from income, following Roberts et. al. (1991) who illustrate the case of having or not having a landfill. In the paired comparison experiment of Swallow et. al. (1994) and Opaluch et. al. (1993), the reference level is not the existence of a landfill, which is compared to the utility gain from not having it., but instead the choice is between two alternative landfills with different characteristics and costs. Each landfill choice has a different fee so $\boldsymbol{A}$ need not be positive, and there is not necessarily any a-priori utility dominance assigned to one attribute set over the other. The respondent just compares the attributes of the two choices and their respective fees and chooses the preferred option.

linear approximation can then be simply written[28] as:

(7) $[\mathbb{M}\boldsymbol{v}(\boldsymbol{z},\boldsymbol{y})/\mathbb{M}\boldsymbol{z}] - [\mathbb{M}\boldsymbol{v}(\boldsymbol{z},\boldsymbol{y})/\mathbb{M}\boldsymbol{y}]A + e_2 \ \$ \ e_1$

There is a value of $A$ that makes the above an equality. Solving for $A$ we get the compensating variation or willingness to pay for the preferred choice:

(8) $$A = [\mathbb{M}\boldsymbol{v}(\boldsymbol{z},\boldsymbol{y})/\mathbb{M}\boldsymbol{z}]/[\mathbb{M}\boldsymbol{v}(\boldsymbol{z},\boldsymbol{y})/\mathbb{M}\boldsymbol{y}] + (e_2 - e_1)/[\mathbb{M}\boldsymbol{v}(\boldsymbol{z},\boldsymbol{y})/\mathbb{M}\boldsymbol{y}]$$

Since the expected value of the sum of two random variables is the sum of their expected values[29], and both $e_2$ and $e_1$ have zero expectation, the expected value of $A$ is the first term in the above expression. In words, willingness to pay is the change in utility occassioned by the change in the site attribute bundle (the numerator of the first term on the r.h.s. of (8), monetized by the marginal utility of income (the denominator of the same term). So, if an econometric estimate of the parameters of the indirect utility function can be obtained, it is possible to get a estimate of the expected value of $A$. This turns out to be fairly straightforward.

## The Logit Model

Each individual in the survey sample is faced with a choice between two alternatives having different attributes and costs. Define an unobserved latent random variable $\mathbf{I_i}^*$ that reflects the level of indirect utility associated with each choice (i indexes Choice 1 or 2). From above this means:

(9.a) $\mathbf{I_1}^* = \boldsymbol{v}(\boldsymbol{z}_1,\boldsymbol{y}) + e_1$

and

(9.b) $\mathbf{I_2}^* = \boldsymbol{v}(\boldsymbol{z}_2,\boldsymbol{y} - A) + e_2$

The observed values of the index $\mathbf{I_i}$ indicate which choice yields the maximum value of the utility index (See Madalla 1983, p. 60):

(10.a) $\mathbf{I_i} = 1$ if $\mathbf{I_i}^* = \text{Max}(\mathbf{I_1}^*,\mathbf{I_2}^*)$

(10.b) $\mathbf{I_i} = 0$ otherwise

Although neither utility level can be observed directly, from (9.a and b) the value of the latent index can be expressed as a function of the attributes of the choices and, optionally, the characteristics of the individuals making them to incorporate systematic differences in the function across socioeconomic groups. Using a linear approximation, in the two states we have, for any individual:

(11.a) $$\mathbf{I_1}^* = \boldsymbol{v}(\boldsymbol{z}_1,\boldsymbol{y}) + e_1 = \mathbf{a_1} + \mathbf{?y} + e_1$$

(11.b) $$\mathbf{I_2}^* = \boldsymbol{v}(\boldsymbol{z}_2,\boldsymbol{y} - A) + e_2 = \mathbf{a_2} + \mathbf{?(y} - A\mathbf{)} + e_2$$

The probability of Choice 2 occurring is, from Eq. (4):

(12) $$\text{Prob } \mathbf{I_2} = 1 = \text{Prob}[e_1 - e_2 < \boldsymbol{v}(\boldsymbol{z}_2,\boldsymbol{y} - A) - \boldsymbol{v}(\boldsymbol{z}_1,\boldsymbol{y})]$$

Substituting the linear approximations for utility in the two states (10.a and 10.b) on the r.h.s. of the inequality (12) gives the probability of Choice 2 in utility difference form (see Hanemann 1984)[30]:

(13) $$\text{Prob } \mathbf{I_2} = 1 = \text{Prob}[e_1 - e_2 < (\mathbf{a_2} - \mathbf{a_1}) - \mathbf{?}A]$$

It can be shown that if the independent error terms $e_1$ and $e_2$ have Weibull distributions, the difference between two random variables with this distribution

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[28] Although they do not explicitly say so, this is the reason Johansson et. al. (1989) show their linear approximation (Eq. 4) without a ***dz*** term.

[29] For a proof, see Larsen and Marx (1981), Theorem 3.7, pp.108-9.

[30] Note that the level of income drops out of the utility difference function when a linear approximation of the latent indirect utility index is used. This is called the "no income effects " RUM (Random Utility Model) which implies that the marginal utility of income is constant and equal to **?**. See Ardila (1993) for an explanation of models that do not impose this restriction.

has a logistic distribution function.[31] Consequently, the probability of Choice 2 produces the binary logit model:

(14) Prob $\mathbf{I}_2 = 1$
$= 1 / (1 + e^{-[(\mathbf{a2} - \mathbf{a1}) - ?A]})$

The parameters of the index function appearing in the exponent of the denominator of (14) can be estimated by maximum likelihood.[32] Theoretically, the sign of the estimate of **?** should be negative, since subtractions from income decrease utility.

Based on Eq. (8) above the expected value (the average) of willingness to pay (WTP) in the absence of income effects is be obtained using the parameter estimates:

(15) $E(WTP) = (\mathbf{a}_2 - \mathbf{a}_1) / \mathbf{?}$

where $\partial \boldsymbol{v}(\boldsymbol{z},\boldsymbol{y})/\partial \boldsymbol{z}$ equals $(\mathbf{a}_2 - \mathbf{a}_1)$ and $\partial \boldsymbol{v}(\boldsymbol{z},\boldsymbol{y})/\partial \boldsymbol{y}$ equals **?**. With this simple model specification, the average WTP equals the median (the point of indifference where the probability of either choice is 0.5) because, solving for *A*, we get the result explained in Eq (15) above:[33]

In a richer formulation, **a** can be expressed as a linear function of a $j = 1...J$ dimensional vector of specific site chacteristics (including an intercept vector of ones for $j$=1), **Z**, so **a** = **ßZ**. Then, (15) above becomes:

(16) $A = [(ß_{21}-ß_{11}) + ß_2(z_{22}-z_{12}) + ß_3(z_{23}-z_{13})...+...ß_{j=J}(z_{2J}-z_{1J})] / ?$

Eq. (16) demonstrates the the monetary equivalent of a utility difference can only be measured *relative* to the attributes associated with the 1th choice reference level, as noted in the main text and the calculations in Appendix 3.[34]

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[31] The proof is quite tedious. See Dhrymes (1978), pp.340-44 or Madalla (1983), p.60.

[32] Only the difference between $a_2$ and $a_1$ can be estimated.

[33] The probability at the median is $0.5 = (1 + e^{-[(\mathbf{a2} - \mathbf{a1}) - ?A]})^{-1}$ or, taking the recriprocal of both sides, rearranging, $1.0 = e^{-[(\mathbf{a2} - \mathbf{a1}) - ?A]}$. Taking logs (note $e^0 = 1$) and solving $A = (\mathbf{a}_2 - \mathbf{a}_1) / \mathbf{?}$.

[34] For a much more detailed explanation of the random utility model and the marginal and non-marginal welfare measures associated with it see Vaughan (1987).

# Appendix 3. Hypothetical Calculations of Site Disutility

| SITE: | #1. ST. ANDREW/KMA | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| LANDFILL SIZE (tpd/total acres): | Attribute Coefficient | 100/159 | | 200/252 | | 500/498 | | 850/763 | |
| Site Attributes | | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score |
| Marsh (Acres) | -0.000310 | 10 | -0.003072 | 16 | -0.004854 | 31 | -0.009592 | 47 | -0.014715 |
| Farm Land (Acres) | -0.004910 | 1 | -0.004669 | 2 | -0.007377 | 3 | -0.014576 | 5 | -0.022361 |
| Groundwater Quality (1=hi;0=lo) | -1.170000 | 1 | -1.17 | 1 | -1.17 | 1 | -1.17 | 1 | -1.17 |
| Wildlife Habitat (1=unique;0=normal) | -0.037100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ponds (Acres) | -0.021760 | 2 | -0.04455 | 3 | -0.070392 | 6 | -0.13909 | 10 | -0.213376 |
| Marsh x Ponds (Sq. Acres) | -0.000391 | 20 | -0.007933 | 51 | -0.019807 | 198 | -0.077333 | 465.4593 | -0.181995 |
| Groundwater Qual. x Ponds (acres) | -0.021550 | 2 | -0.04412 | 3 | -0.069713 | 6 | -0.137748 | 10 | -0.211317 |
| Groundwater Qual. x Marsh (acres) | -0.001700 | 10 | -0.016848 | 16 | -0.026621 | 31 | -0.052601 | 47 | -0.080695 |
| Site Sub-score: | | | -1.291191 | | -1.368763 | | -1.60094 | | -1.894458 |
| Location Attributes | | | | | | | | | |
| Home Density (#per 4 sq. miles) | -0.000772 | 946 | -0.730312 | 946 | -0.730312 | 946 | -0.730312 | 946 | -0.730312 |
| Parkland (1=yes;0=no) | -0.449000 | 1 | -0.449 | 1 | -0.449 | 1 | -0.449 | 1 | -0.449 |
| Farms (1=yes;0=no) | -0.732000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Schools (1=yes;0=no) | -0.751000 | 1 | -0.751 | 1 | -0.751 | 1 | -0.751 | 1 | -0.751 |
| Highway Access (1=no;0=yes) | -0.493000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Location Sub-score: | | | -1.930312 | | -1.930312 | | -1.930312 | | -1.930312 |
| | | | | | | | | | |
| Cost (?) | -0.01322 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Utility Index Score: | | | -3.2215032502 | | -3.299075459 | | -3.5312523453 | | -3.82476951635 |

| SITE: | #2. CLARENDON | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| LANDFILL SIZE (tpd/total acres): | Attribute Coefficient | 100/159 | | 200/252 | | 500/498 | | 850/763 | |
| Site Attributes | | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score |
| Marsh (Acres) | -0.000310 | 90 | -0.027783 | 142 | -0.043899 | 280 | -0.086743 | 429 | -0.13307 |
| Farm Land (Acres) | -0.004910 | 3 | -0.016143 | 5 | -0.025507 | 10 | -0.0504 | 16 | -0.077318 |
| Groundwater Quality (1=hi;0=lo) | -1.170000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Wildlife Habitat (1=unique;0=normal) | -0.037100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ponds (Acres) | -0.021760 | 1 | -0.028485 | 2 | -0.045009 | 4 | -0.088934 | 6 | -0.136433 |
| Marsh x Ponds (Sq. Acres) | -0.000391 | 117 | -0.045872 | 293 | -0.114528 | 1144 | -0.447156 | 2691.401 | -1.052338 |
| Groundwater Qual. x Ponds (acres) | -0.021550 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Groundwater Qual. x Marsh (acres) | -0.001700 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Site Sub-score: | | | -0.118283 | | -0.228943 | | -0.673233 | | -1.399159 |
| Location Attributes | | | | | | | | | |
| Home Density (#per 4 sq. miles) | -0.000772 | 981 | -0.757332 | 981 | -0.757332 | 981 | -0.757332 | 981 | -0.757332 |
| Parkland (1=yes;0=no) | -0.449000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Farms (1=yes;0=no) | -0.732000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Schools (1=yes;0=no) | -0.751000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Highway Access (1=no;0=yes) | -0.493000 | 1 | -0.493 | 1 | -0.493 | 1 | -0.493 | 1 | -0.493 |
| Location Sub-score: | | | -1.250332 | | -1.250332 | | -1.250332 | | -1.250332 |
| | | | | | | | | | |
| Cost ( ?) | -0.01322 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Utility Index Score: | | | -1.3686153066 | | -1.4792747344 | | -1.9235649685 | | -2.64949052779 |

| SITE: | #3. MANCHESTER | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| LANDFILL SIZE (tpd/total acres): | Attribute Coefficient | 100/159 | | 200/252 | | 500/498 | | 850/763 | |
| Site Attributes | | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score |
| Marsh (Acres) | -0.000310 | 66 | -0.020449 | 104 | -0.032311 | 206 | -0.063845 | 316 | -0.097944 |
| Farm Land (Acres) | -0.004910 | 8 | -0.038993 | 13 | -0.061612 | 25 | -0.121741 | 38 | -0.18676 |
| Groundwater Quality (1=hi;0=lo) | -1.170000 | 1 | -1.17 | 1 | -1.17 | 1 | -1.17 | 1 | -1.17 |
| Wildlife Habitat (1=unique;0=normal) | -0.037100 | 1 | -0.0371 | 1 | -0.0371 | 1 | -0.0371 | 1 | -0.0371 |
| Ponds (Acres) | -0.021760 | 9 | -0.203886 | 15 | -0.322156 | 29 | -0.636562 | 45 | -0.976537 |
| Marsh x Ponds (Sq. Acres) | -0.000391 | 618 | -0.241668 | 1543 | -0.603362 | 6025 | -2.355731 | 14178.99 | -5.543986 |
| Groundwater Qual. x Ponds (acres) | -0.021550 | 9 | -0.201918 | 15 | -0.319047 | 29 | -0.630418 | 45 | -0.967113 |
| Groundwater Qual. x Marsh (acres) | -0.001700 | 66 | -0.112141 | 104 | -0.177191 | 206 | -0.350119 | 316 | -0.537111 |
| Site Sub-score: | | | -2.026155 | | -2.722779 | | -5.365517 | | -9.516552 |
| Location Attributes | | | | | | | | | |
| Home Density (#per 4 sq. miles) | -0.000772 | 665 | -0.51338 | 665 | -0.51338 | 665 | -0.51338 | 665 | -0.51338 |
| Parkland (1=yes;0=no) | -0.449000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Farms (1=yes;0=no) | -0.732000 | 1 | -0.732 | 1 | -0.732 | 1 | -0.732 | 1 | -0.732 |
| Schools (1=yes;0=no) | -0.751000 | 1 | -0.751 | 1 | -0.751 | 1 | -0.751 | 1 | -0.751 |
| Highway Access (1=no;0=yes) | -0.493000 | 1 | -0.493 | 1 | -0.493 | 1 | -0.493 | 1 | -0.493 |
| Location Sub-score: | | | -2.48938 | | -2.48938 | | -2.48938 | | -2.48938 |
| | | | | | | | | | |
| Cost ( ?) | -0.01322 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Utility Index Score: | | | -4.5155346905 | | -5.2121593637 | | -7.8548972165 | | -12.0059315183 |

| SITE: | #4. WESTMORELAND | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| LANDFILL SIZE (tpd/total acres): | Attribute Coefficient | 100/159 | | 200/252 | | 500/498 | | 850/763 | |
| Site Attributes | | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score |
| Marsh (Acres) | -0.000310 | 12 | -0.003593 | 18 | -0.005677 | 36 | -0.011217 | 56 | -0.017208 |
| Farm Land (Acres) | -0.004910 | 44 | -0.216549 | 70 | -0.342165 | 138 | -0.676098 | 211 | -1.037188 |
| Groundwater Quality (1=hi;0=lo) | -1.170000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Wildlife Habitat (1=unique;0=normal) | -0.037100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ponds (Acres) | -0.021760 | 27 | -0.582204 | 42 | -0.91993 | 84 | -1.817728 | 128 | -2.788541 |
| Marsh x Ponds (Sq. Acres) | -0.000391 | 310 | -0.121245 | 774 | -0.302707 | 3023 | -1.181872 | 7113.612 | -2.781422 |
| Groundwater Qual. x Ponds (acres) | -0.021550 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Groundwater Qual. x Marsh (acres) | -0.001700 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Site Sub-score: | | | -0.923591 | | -1.570479 | | -3.686915 | | -6.624359 |
| Location Attributes | | | | | | | | | |
| Home Density (#per 4 sq. miles) | -0.000772 | 639 | -0.493308 | 639 | -0.493308 | 639 | -0.493308 | 639 | -0.493308 |
| Parkland (1=yes;0=no) | -0.449000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Farms (1=yes;0=no) | -0.732000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Schools (1=yes;0=no) | -0.751000 | 1 | -0.751 | 1 | -0.751 | 1 | -0.751 | 1 | -0.751 |
| Highway Access (1=no;0=yes) | -0.493000 | 1 | -0.493 | 1 | -0.493 | 1 | -0.493 | 1 | -0.493 |
| Location Sub-score: | | | -1.737308 | | -1.737308 | | -1.737308 | | -1.737308 |
| | | | | | | | | | |
| Cost ( ?) | -0.01322 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Utility Index Score: | | | -2.6608992549 | | -3.3077869471 | | -5.4242228568 | | -8.36166748588 |

| SITE: | #5. ST. JAMES | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| LANDFILL SIZE (tpd/total acres): | Attribute Coefficient | 100/159 | | 200/252 | | 500/498 | | 850/763 | |
| Site Attributes | | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score |
| Marsh (Acres) | -0.000310 | 37 | -0.011446 | 58 | -0.018086 | 115 | -0.035736 | 177 | -0.054822 |
| Farm Land (Acres) | -0.004910 | 4 | -0.0218 | 7 | -0.034445 | 14 | -0.068062 | 21 | -0.104412 |
| Groundwater Quality (1=hi;0=lo) | -1.170000 | 1 | -1.17 | 1 | -1.17 | 1 | -1.17 | 1 | -1.17 |
| Wildlife Habitat (1=unique;0=normal) | -0.037100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ponds (Acres) | -0.021760 | 15 | -0.316702 | 23 | -0.500416 | 45 | -0.988792 | 70 | -1.516886 |
| Marsh x Ponds (Sq. Acres) | -0.000391 | 537 | -0.210117 | 1342 | -0.524591 | 5238 | -2.048182 | 12327.88 | -4.820199 |
| Groundwater Qual. x Ponds (acres) | -0.021550 | 15 | -0.313646 | 23 | -0.495586 | 45 | -0.979249 | 70 | -1.502247 |
| Groundwater Qual. x Marsh (acres) | -0.001700 | 37 | -0.062768 | 58 | -0.099179 | 115 | -0.195972 | 177 | -0.300637 |
| Site Sub-score: | | | -2.10648 | | -2.842303 | | -5.485993 | | -9.469204 |
| Location Attributes | | | | | | | | | |
| Home Density (#per 4 sq. miles) | -0.000772 | 797 | -0.615284 | 797 | -0.615284 | 797 | -0.615284 | 797 | -0.615284 |
| Parkland (1=yes;0=no) | -0.449000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Farms (1=yes;0=no) | -0.732000 | 1 | -0.732 | 1 | -0.732 | 1 | -0.732 | 1 | -0.732 |
| Schools (1=yes;0=no) | -0.751000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Highway Access (1=no;0=yes) | -0.493000 | 1 | -0.493 | 1 | -0.493 | 1 | -0.493 | 1 | -0.493 |
| Location Sub-score: | | | -1.840284 | | -1.840284 | | -1.840284 | | -1.840284 |
| | | | | | | | | | |
| Cost (?) | -0.01322 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Utility Index Score: | | | -3.9467641454 | | -4.6825865894 | | -7.3262773361 | | -11.3094881078 |

| SITE: | #6. TRELAWNY | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| LANDFILL SIZE (tpd/total acres): | Attribute Coefficient | 100/159 | | 200/252 | | 500/498 | | 850/763 | |
| Site Attributes | | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score |
| Marsh (Acres) | -0.000310 | 72 | -0.022417 | 114 | -0.035421 | 226 | -0.069989 | 346 | -0.107369 |
| Farm Land (Acres) | -0.004910 | 4 | -0.020418 | 7 | -0.032263 | 13 | -0.063749 | 20 | -0.097796 |
| Groundwater Quality (1=hi;0=lo) | -1.170000 | 1 | -1.17 | 1 | -1.17 | 1 | -1.17 | 1 | -1.17 |
| Wildlife Habitat (1=unique;0=normal) | -0.037100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ponds (Acres) | -0.021760 | 20 | -0.426955 | 31 | -0.674623 | 61 | -1.333015 | 94 | -2.044953 |
| Marsh x Ponds (Sq. Acres) | -0.000391 | 1419 | -0.554773 | 3542 | -1.385077 | 13831 | -5.407816 | 32549.29 | -12.72677 |
| Groundwater Qual. x Ponds (acres) | -0.021550 | 20 | -0.422834 | 31 | -0.668112 | 61 | -1.320151 | 94 | -2.025218 |
| Groundwater Qual. x Marsh (acres) | -0.001700 | 72 | -0.122932 | 114 | -0.194242 | 226 | -0.383811 | 346 | -0.588798 |
| Site Sub-score: | | | -2.740329 | | -4.159738 | | -9.748531 | | -18.7609 |
| Location Attributes | | | | | | | | | |
| Home Density (#per 4 sq. miles) | -0.000772 | 544 | -0.419968 | 544 | -0.419968 | 544 | -0.419968 | 544 | -0.419968 |
| Parkland (1=yes;0=no) | -0.449000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Farms (1=yes;0=no) | -0.732000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Schools (1=yes;0=no) | -0.751000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Highway Access (1=no;0=yes) | -0.493000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Location Sub-score: | | | -0.419968 | | -0.419968 | | -0.419968 | | -0.419968 |
| | | | | | | | | | |
| Cost (?) | -0.01322 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Utility Index Score: | | | -3.1602971491 | | -4.5797057684 | | -10.168499003 | | -19.1808725274 |

| SITE: | #7. ST. ANN | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| LANDFILL SIZE (tpd/total acres): | Attribute Coefficient | 100/159 | | 200/252 | | 500/498 | | 850/763 | |
| | | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score |
| Site Attributes | | | | | | | | | |
| Marsh (Acres) | -0.000310 | 1 | -0.000309 | 2 | -0.000487 | 3 | -0.000963 | 5 | -0.001478 |
| Farm Land (Acres) | -0.004910 | 3 | -0.012752 | 4 | -0.02015 | 8 | -0.039815 | 12 | -0.061079 |
| Groundwater Quality (1=hi;0=lo) | -1.170000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Wildlife Habitat (1=unique;0=normal) | -0.037100 | 1 | -0.0371 | 1 | -0.0371 | 1 | -0.0371 | 1 | -0.0371 |
| Ponds (Acres) | -0.021760 | 0 | -0.001899 | 0 | -0.003001 | 0 | -0.00593 | 0 | -0.009098 |
| Marsh x Ponds (Sq. Acres) | -0.000391 | 0 | -0.000034 | 0 | -0.000085 | 1 | -0.000331 | 1.992925 | -0.000779 |
| Groundwater Qual. x Ponds (acres) | -0.021550 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Groundwater Qual. x Marsh (acres) | -0.001700 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Site Sub-score: | | | -0.052094 | | -0.060823 | | -0.084139 | | -0.109534 |
| Location Attributes | | | | | | | | | |
| Home Density (#per 4 sq. miles) | -0.000772 | 457 | -0.352804 | 457 | -0.352804 | 457 | -0.352804 | 457 | -0.352804 |
| Parkland (1=yes;0=no) | -0.449000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Farms (1=yes;0=no) | -0.732000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Schools (1=yes;0=no) | -0.751000 | 1 | -0.751 | 1 | -0.751 | 1 | -0.751 | 1 | -0.751 |
| Highway Access (1=no;0=yes) | -0.493000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Location Sub-score: | | | -1.103804 | | -1.103804 | | -1.103804 | | -1.103804 |
| | | | | | | | | | |
| Cost (?) | -0.01322 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Utility Index Score: | | | ?? | | ?? | | ?? | | ?? |

| SITE: | #8. ST. MARY | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| LANDFILL SIZE (tpd/total acres): | Attribute Coefficient | 100/159 | | 200/252 | | 500/498 | | 850/763 | |
| Site Attributes | | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score |
| Marsh (Acres) | -0.000310 | 74 | -0.02299 | 117 | -0.036326 | 232 | -0.071779 | 355 | -0.110114 |
| Farm Land (Acres) | -0.004910 | 3 | -0.013371 | 4 | -0.021127 | 9 | -0.041745 | 13 | -0.064041 |
| Groundwater Quality (1=hi;0=lo) | -1.170000 | 1 | -1.17 | 1 | -1.17 | 1 | -1.17 | 1 | -1.17 |
| Wildlife Habitat (1=unique;0=normal) | -0.037100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Ponds (Acres) | -0.021760 | 5 | -0.107657 | 8 | -0.170106 | 15 | -0.33612 | 24 | -0.515635 |
| Marsh x Ponds (Sq. Acres) | -0.000391 | 367 | -0.143463 | 916 | -0.358177 | 3577 | -1.398448 | 8417.166 | -3.291112 |
| Groundwater Qual. x Ponds (acres) | -0.021550 | 5 | -0.106618 | 8 | -0.168465 | 15 | -0.332876 | 24 | -0.510659 |
| Groundwater Qual. x Marsh (acres) | -0.001700 | 74 | -0.126075 | 117 | -0.199209 | 232 | -0.393626 | 355 | -0.603853 |
| Site Sub-score: | | | -1.690173 | | -2.12341 | | -3.744593 | | -6.265414 |
| Location Attributes | | | | | | | | | |
| Home Density (#per 4 sq. miles) | -0.000772 | 241 | -0.186052 | 241 | -0.186052 | 241 | -0.186052 | 241 | -0.186052 |
| Parkland (1=yes;0=no) | -0.449000 | 1 | -0.449 | 1 | -0.449 | 1 | -0.449 | 1 | -0.449 |
| Farms (1=yes;0=no) | -0.732000 | 1 | -0.732 | 1 | -0.732 | 1 | -0.732 | 1 | -0.732 |
| Schools (1=yes;0=no) | -0.751000 | 1 | -0.751 | 1 | -0.751 | 1 | -0.751 | 1 | -0.751 |
| Highway Access (1=no;0=yes) | -0.493000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Location Sub-score: | | | -2.118052 | | -2.118052 | | -2.118052 | | -2.118052 |
| | | | | | | | | | |
| Cost (?) | -0.01322 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Utility Index Score: | | | ?? | | ?? | | ?? | | ?? |

| SITE: | #9. PORTLAND | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| LANDFILL SIZE (tpd/total acres): | Attribute Coefficient | 100/159 | | 200/252 | | 500/498 | | 850/763 | |
| Site Attributes | | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score | Attribute Level | Attribute Score |
| Marsh (Acres) | -0.000310 | 14 | -0.004382 | 22 | -0.006923 | 44 | -0.01368 | 68 | -0.020987 |
| Farm Land (Acres) | -0.004910 | 46 | -0.224473 | 72 | -0.354685 | 143 | -0.700837 | 219 | -1.075141 |
| Groundwater Quality (1=hi;0=lo) | -1.170000 | 1 | -1.17 | 1 | -1.17 | 1 | -1.17 | 1 | -1.17 |
| Wildlife Habitat (1=unique;0=normal) | -0.037100 | 1 | -0.0371 | 1 | -0.0371 | 1 | -0.0371 | 1 | -0.0371 |
| Ponds (Acres) | -0.021760 | 16 | -0.34243 | 25 | -0.541067 | 49 | -1.069117 | 75 | -1.640111 |
| Marsh x Ponds (Sq. Acres) | -0.000391 | 222 | -0.086971 | 555 | -0.217137 | 2168 | -0.847776 | 5102.706 | -1.995158 |
| Groundwater Qual. x Ponds (acres) | -0.021550 | 16 | -0.339125 | 25 | -0.535845 | 49 | -1.058799 | 75 | -1.624283 |
| Groundwater Qual. x Marsh (acres) | -0.001700 | 14 | -0.024029 | 22 | -0.037968 | 44 | -0.075022 | 68 | -0.115089 |
| Site Sub-score: | | | -2.22851 | | -2.900725 | | -4.972331 | | -7.677869 |
| Location Attributes | | | | | | | | | |
| Home Density (#per 4 sq. miles) | -0.000772 | 241 | -0.186052 | 241 | -0.186052 | 241 | -0.186052 | 241 | -0.186052 |
| Parkland (1=yes;0=no) | -0.449000 | 1 | -0.449 | 1 | -0.449 | 1 | -0.449 | 1 | -0.449 |
| Farms (1=yes;0=no) | -0.732000 | 1 | -0.732 | 1 | -0.732 | 1 | -0.732 | 1 | -0.732 |
| Schools (1=yes;0=no) | -0.751000 | 1 | -0.751 | 1 | -0.751 | 1 | -0.751 | 1 | -0.751 |
| Highway Access (1=no;0=yes) | -0.493000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Location Sub-score: | | | -2.118052 | | -2.118052 | | -2.118052 | | -2.118052 |
| | | | | | | | | | |
| Cost (?) | -0.01322 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Utility Index Score: | | | ?? | | ?? | | ?? | | ?? |

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