

# Optimal Siting of Regional Fecal Sludge Treatment Facilities: St. Elizabeth, Jamaica

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**Abstract:** In the developing nation of Jamaica, 70% of the population depends upon on-site sanitation systems, which can provide an effective and low-cost option for rural wastewater treatment. However, there are serious environmental and human health effects associated with their mismanagement and deterioration. Historically, fecal sludge management has been addressed as a localized problem. Instead, we introduce a regional decision model of FS treatment options. The problem is formulated as a mixed-integer programming model, which selects the optimal combination of treatment, hauling, and pumping options and their locations based on a variety of social and economic constraints. The constraint method of optimization led to an optimal trade-off curve between the number of people negatively affected and the cost of a given management plan. A sensitivity analysis documents model sensitivity to capital cost variation among potential treatment sites.

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**CE Database subject headings:** Sludge; System analysis; Waste stabilization ponds; Wastewater management; Optimization; Jamaica.

## Introduction

In the developing nation of Jamaica, 70% of the population depends on on-site sanitation facilities such as septic tanks, soak-away pits or pit latrines for wastewater treatment. Fecal sludge (FS) is defined as the sludge of variable consistency collected from on-site sanitation systems (OSSs) and consisting of varying concentrations of settleable or settled solids (Heinss et al. 1998). Uncontrolled and indiscriminate dumping of FS removed from on-site systems is commonplace in many regions of Jamaica. The mismanagement of FS can result in numerous impacts to the environmental and water resources of a region. It is important to note that Jamaica consists primarily of Karstic limestone, a medium that allows for rapid infiltration to the groundwater table. Jamaicans are dependent almost entirely on groundwater, therefore the potential for drinking-water contamination by untreated FS is evident. Mismanagement also creates the potential for human health risks through human contact with untreated FS, as well as the contamination of other environmental and water resources such as rivers, lakes, soils, and groundwater aquifers (VanHoven 2004).

In the parish of St. Elizabeth (approximately 1,200 km<sup>2</sup>) no FS treatment facilities exist, and the distance to existing facilities outside the parish renders hauling cost prohibitive. When the sludge from OSSs is emptied, there is general uncertainty as to its ultimate disposal.

The Ministry of Health (MoH) of Jamaica recently began a study of island-wide septage management, and is in the process of developing guidelines for the licensing of cesspool operators. The MoH also plans to develop a framework for licensing haulers and regulations for the dumping of FS (R. Chmielewski, e-mail communication, 2004). To this end, the following study was conducted from the perspective of the St. Elizabeth Parish Council, with the goal of determining suitable areas for local FS treatment systems and ultimately selecting an optimum combination of FS treatment options for the region. The model was developed to be used in conjunction with a management plan developed by the Government of Jamaica and may also be expanded to enable island-wide FS management.

We were unable to find examples in the literature of a systematic analysis applied to sludge management, hence, another goal of this work was to develop what appears to be the first study to develop a systems model for the improved management of sludge removed from on-site sanitation systems. This study differs from previous studies where the treatment and disposal of FS was addressed as a localized problem. Instead, our goal is to develop an integrated systems approach that borrows from similar approaches applied to both land application of sludge (Crohn and Thomas 1998) and wastewater systems (Phillips et al. 1982).

## Background: St. Elizabeth, Jamaica

The island nation of Jamaica, West Indies is located in the Caribbean Sea approximately 160 km south of Cuba. The island is approximately 10,830 km<sup>2</sup> and consists of predominantly mountainous terrain, with narrow and discontinuous coastal plains. Approximately 5.6% of the national population (in the

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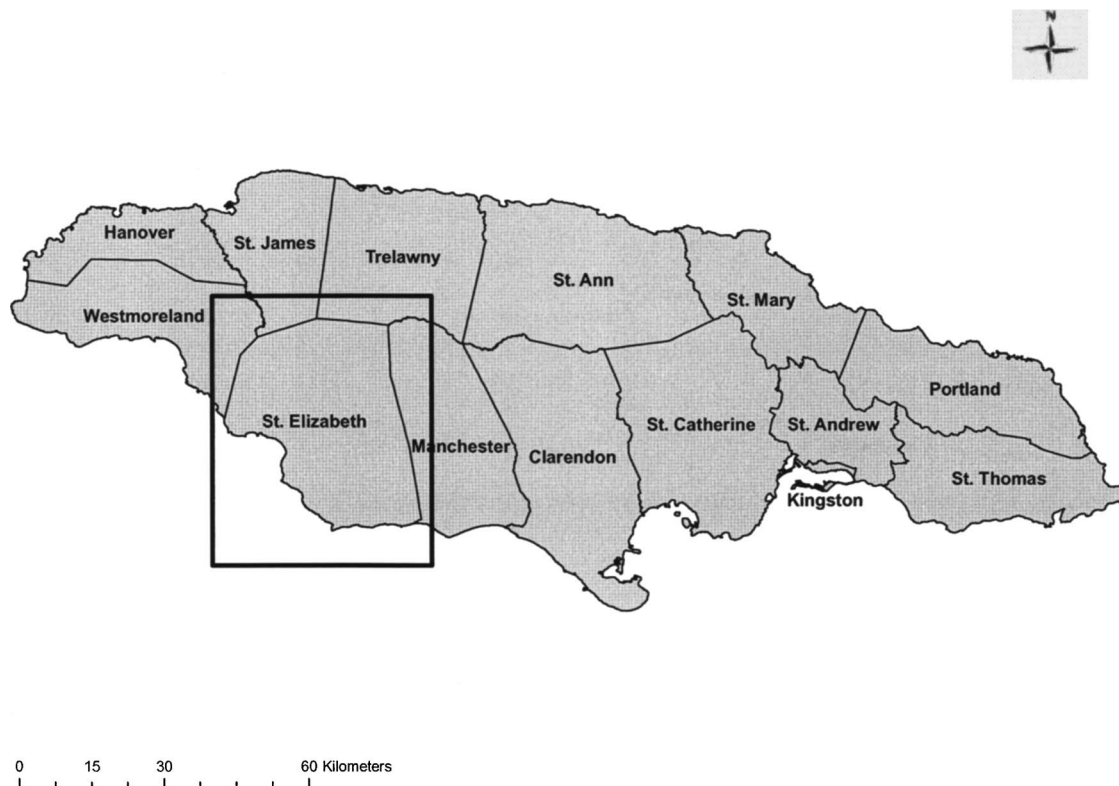


Fig. 1. Location map, St. Elizabeth, Jamaica

2001 Census, 146,391 people) resides in St. Elizabeth (see Fig. 1), with 69% in rural areas of the parish and 31% in the major towns and cities (Statistical Institute of Jamaica 2001). The parish relies almost exclusively on on-site systems for sanitation.

As in most small island states, the economic livelihood and social well being of the Jamaican people depends heavily on its fresh and salt water resources. A majority of Jamaica's foreign exchange is earned through tourism and agriculture for primary production.

### Literature Review on Mathematical Programming and Fecal Sludge

In the past, the treatment and disposal of FS removed from OSSs has been addressed as a localized problem in Jamaica. Since few examples exist in the literature of a systematic analysis applied to sludge management, our literature review focuses on the application of mathematical programming methods to similar systems, such as wastewater sludge and solid waste disposal and planning of centralized wastewater treatment systems.

Systematic analyses of centralized water and wastewater systems generally employ some form of material flow analysis (using the principle of conservation of mass) in conjunction with optimization and heuristic algorithms. Crohn and Thomas (1998) used a mixed-integer program to minimize the costs of sewage sludge management by various land application technologies for a county in California. Options included digestion, biosolids storage, trucking, composting, and landspreading. This study incorporated various treatment methods and potential locations and, hence, variable capital, operation, and maintenance costs, in order to determine the distribution of sludge to be sent to digesters, compost, or landspreading. Because there is only one feasible

treatment method for all sites in Jamaica, our model incorporates only one treatment method at each site. This is subsequently discussed.

In the field of wastewater network planning, the use of optimization and heuristic algorithms has been extensive (Mandl 1981). McConagha and Converse (1973) employed a heuristic design and cost allocation algorithm. The model's objective was to determine the number and location of wastewater treatment plants and the sewer networks required, using a hypothetical region along one river. The model included a nonlinear cost function, exhibiting economies of scale.

Ellis and Tang (1991) used a nonlinear mixed integer programming model to optimize wastewater treatment systems in the developing world, incorporating technical, economic, environmental, social, and cultural factors as indicators. Subjective parameters that affect the operation of wastewater treatment plants were incorporated by developing a hierarchy of objectives and alternatives. The model was then tested with data from several countries. A lack of detailed site-level data for each of the potential treatment sites and the uncertainty in sludge composition prevented our use of a hierarchical structure of decision variables, central to Ellis and Tang's work.

Crohn and Thomas (1998), Phillips et al. (1982), and Leighton and Shoemaker (1984) all used integer programming models to design and update regional wastewater treatment systems. Although literature exists on wastewater sludge and wastewater management, this particular problem of regional FS management is anomalous in comparison with previous applications. As a result of the lack of plot-level information, inherent uncertainties in pumping frequency and sludge quality, and a lack of information surrounding the variable costs of sludge treatment, regional FS management needs remain uncertain.

We employ a mixed-integer linear programming approach to

select the optimal treatment locations for the region and their capacities. The formulation and level of detail incorporated in our model most closely resemble that of Crohn and Thomas (1998) on land application systems and Phillips et al. (1982) on area-wide wastewater management. Similar to this study, Phillips et al. (1982) used mixed integer programming to develop an optimal regional wastewater treatment plan. In their work, the wastewater systems were centralized systems, and the model focused on evaluating trade-offs between building new treatment facilities and developing piping networks to convey waste to existing facilities. To our knowledge, this is the first study that has sought to develop a broad level assessment tool for the integrated assessment of FS treatment strategies in an optimization framework.

## **Integrated Assessment of FS Treatment Options**

The overall methodology introduced here involves three steps: First, an integrated assessment of existing FS management practices in Jamaica was implemented that considered economic and social factors, in addition to technical options. Next, a spatial analysis of wastewater treatment options in Jamaica was compiled using a geographic information system (GIS) and land use information. Finally, using the integrated assessment and spatial analysis, a systems optimization model of FS treatment in Jamaica was developed and optimum combinations of FS treatment options were determined for St. Elizabeth for several possible scenarios. The constraint method was used to develop multiobjective trade-off curves, with the goal of developing a tool for use in planning regional sludge management. Each of these steps is summarized in greater detail in the following sections.

### ***Treatment Options***

In order to assess optimal treatment schemes for FS in the St. Elizabeth region, several treatment options were considered. An initial review of the existing wastewater treatment plant infrastructure in the St. Elizabeth region indicated that it would not be feasible to upgrade existing plants to accept additional solids.

In addition to hauling FS to the existing wastewater treatment plants, the potential for construction of new regional wastewater treatment plants was considered. The cost of building a single regional wastewater treatment plant and installing sewers for each of the census areas, thus converting on-site systems into a single centralized wastewater system, was assumed to be prohibitive.

The construction of new FS treatment systems was considered the only viable option for current FS management needs in the region. The most popular and practical methods of FS stabilization include alkali stabilization, aerobic digestion, anaerobic digestion, and composting. Aerobic digestion systems are the most common type of wastewater treatment in Jamaica and were therefore considered as a viable option.

Whereas active aerobic digestion uses power to operate aeration systems, passive aerobic systems take advantage of the high ambient temperature and sunlight common throughout Jamaica, reducing organic solids content and potential odors. Such systems include sludge drying beds/ponds, constructed wetlands, sedimentation/thickening tanks, waste stabilization ponds, and cotermination ponds for wastewater and FS (Montangero and Strauss 2002).

Sludge drying beds and ponds closely resemble the FS treatment facilities currently used in other areas of Jamaica. They are relatively simple systems that can produce a solids product that

can be reused as fertilizer or soil conditioner if the system is properly designed and operated. Drying beds employ the processes of gravity percolation and evaporation in separating the solids from the liquid in sludge (Montangero and Strauss 2002). Approximately 50–80% of the volume applied to drying beds emerges from the system as drained liquid, or percolate, both of which must subsequently be treated in facultative ponds. Secondary facultative ponds, ponds that receive settled wastewater, are constructed in series with sludge drying beds and drain into an adjacent leaching field.

### ***Sludge Drying Bed Design***

Sludge drying bed systems are designed using the expected volume and total suspended solids concentration of the FS to be treated (Montangero and Strauss 2002). The volume of FS to be treated is calculated from the total population of St. Elizabeth in 2001 of 146,391 people. For each census area, the volume of FS to be treated is calculated using a value of 300 L/capita/year (Klingel et al. 2001; CWRS 1999), approximating the volume of FS produced per person per year. Assuming a typical hauling truck capacity of 1,800 gallons, approximately 1,035 truckloads of FS require treatment in St. Elizabeth each year. In order to account for the drying bed, pond, leaching field, and biosolid storage and equipment storage space, an area of 1.2 ha (3 acres) was assumed necessary for each site.

### ***Land Application and Biosolids Reuse***

After stabilization through aerobic treatment in a drying bed and facultative pond facility, biosolids removed from the beds can be used as fertilizer or soil conditioner, depending on its final characteristics. Construction of a pilot-scale drying bed and pond treatment facility will allow for the typical characteristics of FS to be tested and, in turn, the biosolids removed from the facility can be tested for land application suitability as well as nitrogen and phosphorus content. We assume that biosolids can be sold as soil conditioner and fertilizer.

In future analyses of island-wide FS management in Jamaica, land reclamation of spent bauxite mines should also be considered for treatment facility location. Plot-level information on spent bauxite mines was not available for analysis in this model; however, such information should be included in future management plans. The facilities would consume a small fraction of the bauxite land area and the biosolids produced could then be reused on-site as soil conditioner.

## ***Spatial Analysis for Determination of Parameters***

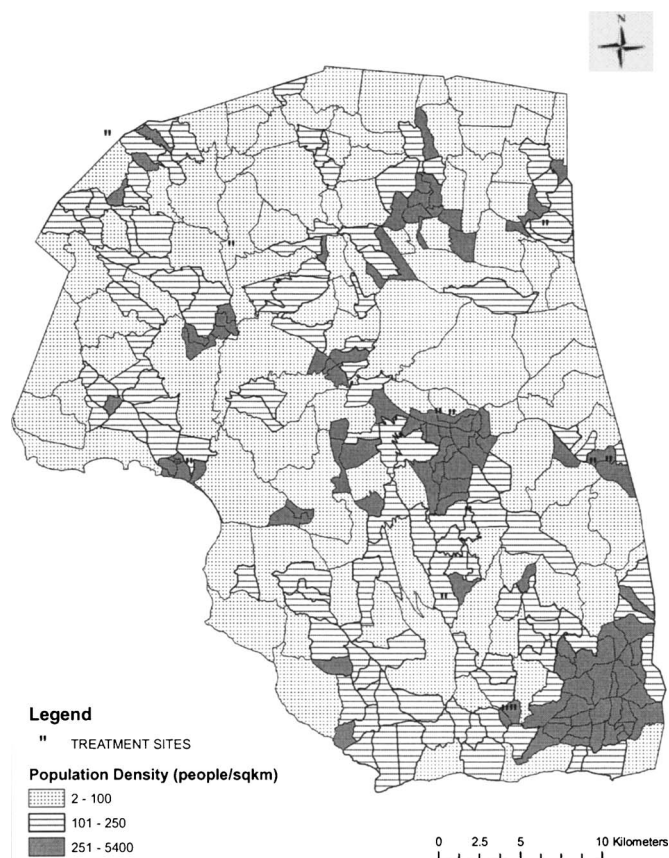
### ***Treatment Site Identification***

Land parcels owned by the parish government (Parish Council) were considered potential sites for the construction of local FS treatment facilities. GIS information regarding parish-owned land parcels was gathered from the Parish Council of St. Elizabeth (Brown, August 2004). Only land parcels currently owned by the parish were considered potential treatment sites.

### ***Site Prefeasibility***

Several site attributes were used to determine areas suitable for the construction of FS treatment facilities including: topography (land slope), soil type, and probability of flooding (GIS data including flood occurrence, soil type, and contours were obtained).





**Fig. 2.** Treatment site locations

The 3 acre restriction on parcel size narrowed the potential treatment sites to 12 locations. Using ArcMap (ArcGIS 2006), the 12 sites were then overlaid with other data gathered in GIS. The assessment of site feasibility considered a number of environmental factors including the criteria of land slope, soil type, and flooding. All of the 12 potential treatment sites were deemed feasible locations and were assigned latitude-longitude values. The map of feasible facility locations is illustrated in Fig. 2.

### Population Data

From the GIS overlay of housing density, census tracts, and roadway files, one location was selected to represent the center of the population in each census area. These population points and the roadway line files were converted from ArcMap point and vector files to raster format using Idrisi Kilimangaro (IDRISI 2006).

### Calculation of Travel Times

A matrix of travel times between the 308 census areas and the 12 treatment sites was developed using the Idrisi cost function for each of the treatment sites. A weighting system was established to represent the difficulty inherent in hauling sludge from rural areas, areas with less access to main roads, and swamp and mangrove areas. Roads were subjectively given a weight of one, areas off road a weight of two, and water bodies were given a weight of 100. The cost function was then calculated 12 times to represent the time of traveling from any of the census raster cells within the parish to a given treatment location.

### Calculation of Affected Population

Using land-use maps from the National Land Agency of Jamaica, hospitals, schools, community centers, churches, and other public buildings were all assigned point locations. For each of the treatment sites, it was assumed that construction and operation of an FS treatment facility would have an area of influence of approximately 3.14 km<sup>2</sup> (using a radius of influence of 1 km). Using ArcMap, the population density was spatially averaged from the population densities in the census areas intersecting the radius of influence.

While the treatment facilities provide a service to the public, each of the treatment sites is contained within a community, and the construction and operation of a facility could potentially have negative effects on the surrounding population. For this reason, consideration of the population immediately surrounding treatment sites was included in the optimization algorithm. The number of people potentially affected by a facility within the assumed 3.14 km<sup>2</sup> area was calculated using the spatial average of population density. In addition to the spatially averaged population density, the weight was increased by 25% for each public building within the affected area.

### Decision Model Formulation

#### Model Scenarios

To provide regulators and citizens with several alternatives for management, and in keeping with the *principle of expediency* (Bartlett and Vesilind 1998), the model was developed considering several potential planning scenarios. In order to minimize hauling distances, prevent the uncontrolled dumping of sludge, and keep land requirements for individual treatment schemes modest, Carr (2001) suggests that collection, hauling, and treatment strategies should focus on decentralized solutions.

Here a decentralized approach is implemented by allowing for the construction of treatment facilities in a variety of locations throughout the parish. The objective in the first scenario is to meet the objective of treating the entire volume of FS produced by allowing for a range of treatment facility sizes. This first scenario considers treatment of the total volume of FS produced, in which case several trucks may be purchased and treatment facilities may be built at any one of the 12 treatment sites. A second scenario considers a multiobjective model in which the cost of treatment and the number of people affected by treatment facility construction are both considered. This scenario employed the constraint method of multiobjective programming to develop an optimal trade-off curve between the number of people negatively affected by a given management plan and the cost of the plan. Finally, sensitivity analysis was performed to determine the effects of variable capital costs associated with the treatment sites. Each of the scenarios is described in further detail in the following sections.

#### Overall Model Structure: Objective Function

The model scenarios were implemented using GAMS IDE Software (GAMSIDE 2000). The costs to be minimized are defined as the difference between the costs incurred from FS management actions taken (construction of a treatment system, operation and maintenance, and hauling costs) and the revenues derived from hauling fees and biosolid sales. The benefits and costs are repre-

sented by present values, assuming an interest rate of 8.5% and a life of ten years. In summary, the net benefits  $Z$  are given by

$$Z = B - C \quad (1)$$

where  $C$ =present value of costs of hauling, construction/operation, and maintenance; and  $B$ =benefits that include service fees levied and the biosolids profits defined as follows:

$$B = \left( \sum_{j=1}^{12} T_j \right) \times S \quad (2)$$

where the variable  $S$ =unit benefit value per truckload (\$/truckload) of sludge treated (as a result of fees levied for the service and biosolids sales); and  $T_j$ =volume of sludge treated at site  $j$  (truckloads). Although the market for biosolids as organic soil conditioners is not certain, current examples of biosolids sales and the use of organic soil conditioners and fertilizers island wide were assessed. Hauling fees were assumed to be the lower bound cited by VanHoven (2004) (J\$1,500–J\$9,000), or approximately J\$1,500/truckload. In addition to this fee for each truckload hauled, it was assumed that some revenue (depending on the market) could also be made from the sale of biosolids. A bag of fertilizer in Jamaica costs approximately J\$500, and it was assumed that approximately one bag of marketable fertilizer would be produced from each truckload treated.

### Net Costs

The objective function also includes the costs associated with hauling sludge, treatment facility construction and operation, and the purchase of hauling trucks,  $C$  as follows:

$$C = U_h \sum_{i=1}^{308} \sum_{j=1}^{12} P_{ij} \times V_i \times d_{ij} + \sum_{j=1}^{12} (T_j \times 6,852) + HT \times Cht \quad (3)$$

where  $U_h$ =unit cost of transporting one truckload (\$/truckload/hr), which includes fuel and maintenance;  $d_{ij}$ =Idrisi weighted time value associated with traveling from census area  $i$  to treatment site  $j$  in hours;  $P_{ij}$ =binary variable (1 if sludge is hauled from  $i$  to  $j$ , 0 if it is not);  $V_i$ =volume of sludge originating from area  $i$  (truckloads);  $T_j$ =volume of sludge treated at site  $j$  (truckloads); the scalar 6,852=linear relationship calculated between truckloads treated and treatment facility cost (explained further in this section); HT=number of hauling trucks; and Cht=present value of the annualized capital cost of a hauling truck.

### Hauling Costs

The unit cost of transporting one truckload of sludge ( $U_h$ ) was calculated using the assumed fuel efficiency and diesel prices in Jamaica. Although no data were available for specific fuel efficiency of hauling/pump trucks, data for garbage trucks were obtained. The average fuel efficiency of 1.28 km/L (or 3 miles/gal) was employed, based upon the assumption that sludge hauling vehicles are similar to garbage trucks in size and weight (Inform 2006). During the summer of 2004, diesel prices in Jamaica were approximately J\$35/l (US\$ 0.58/L, US\$2.21/gal). To account for maintenance, this value was increased to J\$50/L. Using the fuel efficiency of 1.276 km/L, a price of J\$50/L, and assuming an average speed (including idling and slow-moving traffic) of 20 km/h, the cost of traveling for one hour was calculated to be J\$784.

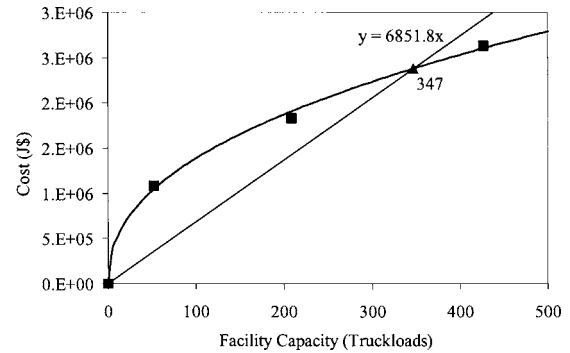


Fig. 3. Facility cost and capacity relationship

A hauling truck operator's hourly salary was also included in the calculation of hauling cost. Skilled laborers in Jamaica charge approximately J\$1,500/day. Assuming approximately 5 h of work each day, a salary of J\$300/h was calculated. The total hourly cost of hauling one truckload  $U_h$  was calculated to be J\$1,084/h (the sum of the costs of fuel and operator salary). Throughout the model, sludge volume is measured in truckloads, as trucks are assumed to haul only full loads of waste.

While no data were available for pump truck costs in Jamaica, we employed data for used pump trucks sold in the United States. Large, used pump trucks (2,500 gal) currently sell for approximately J\$3,600,000 (or US\$60,000). Assuming a smaller, 1,800 gallon truck would be purchased in Jamaica, the cost of each truck was estimated to be J\$6,000,000 (or US\$100,000); it is assumed because of shipping costs and duties that a smaller truck in Jamaica could cost more than a larger truck in the U.S.

### Facility Construction and Operating and Maintenance Costs

The cost for drying bed/facultative pond facilities of different sizes was calculated using estimates for material, labor, and construction costs. Facilities capable of treating 52, 208, and 416 truckloads per year were found to cost approximately J\$429,265, J\$1,182,614, and J\$1,975,455, respectively. These cost calculations were preliminary, using costs for materials such as blocks, cement, sand, gravel, stone, piping, chlorinator, liner, backhoe excavation, and cleanup, as well as construction costs for both the drying bed and the pond. A design fee of 10% and contingency addition of 25% were also incorporated in the estimated costs.

In addition to the capital costs for system construction, annual maintenance costs were included in the analysis. The annual maintenance costs incurred by the cesspool sludge disposal operator interviewed in Clarendon Parish totaled approximately J\$75,000 per year, and to be conservative, this value was increased to J\$100,000. A quadratic relationship was estimated between present-worth cost of facilities and volume treated as shown in Fig. 3, using the three points (shown as squares) representing the present-worth costs of the various treatment facilities discussed above. Using that equation, a linear relationship between cost ( $y$ ) and the total volume of sludge treated  $T_j(x)$ , was calculated and included in the cost function ( $y=6,851.8x$ ). While treatment facilities typically exhibit economies of scale, smaller wastewater systems often do not (Rocky Mountain Institute 2004). Construction of these drying bed systems might be financed through public or private funds or a combination of the two. Currently in Jamaica, operators of existing drying beds have privately financed these disposal systems; however, with the es-

establishment of sludge management regulations, other financing structures, including the provision of government subsidies, should be analyzed.

### Decision Model Structure: Constraints

Calculation of the total volume treated at each treatment site  $j$ ,  $T_j$ , was included in the constraints of the model in order to include the cost of all facilities constructed. The total volume treated at each treatment site  $j$  was set equal to the sum over all census areas  $i$  of the product of the binary variable  $P_{ij}$  (1 if sludge is hauled from  $i$  to  $j$ , 0 if it is not) and  $V_i$ , the volume of sludge originating from area  $i$  (truckloads)

$$T_j = \sum_{i=1}^{308} P_{ij} \times V_i \quad \forall j \quad (4)$$

The volume of sludge originating from each area  $i$  was calculated assuming each household empties their septic tank every 6 years on average. To ensure that all waste is treated, the sum of the volumes originating from each census area  $i$  must be greater than or equal to the volume of sludge being produced in a given census area  $i$

$$\sum_{j=1}^{12} P_{ij} \times V_i \geq V_i \quad (5)$$

where  $P_{ij}$ =binary variable (1 if sludge is hauled from  $i$  to  $j$ , 0 if it is not) and  $V_i$  is the volume of sludge hauled from area  $i$  (truckloads).

There is an upper bound on the distance a hauling truck can travel in one year. This constraint was based on the assumption that hauling trucks would operate approximately 5 hours per day (not including time required for filling and emptying the hauling truck), 5 days per week, and 52 weeks per year. Given these values, one hauling truck can travel approximately 1,300 hours each year. To ensure that an adequate number of hauling trucks HT were purchased

$$HT \geq \sum_{j=1}^{12} \sum_{i=1}^{308} [(0.00149 \times d_{ij}) \times P_{ij} \times V_i \times 2] / 1,300 \quad (6)$$

where  $d_{ij}$ =Idrisi weighted time value associated with traveling from census area  $i$  to treatment site  $j$  calculated in hours;  $P_{ij}$  and  $V_i$  were defined previously, and the scalar 2 is needed because a truck must travel out and back to haul and treat one truckload, and the scalar 1,300 represents the maximum number of hours one truck can travel annually (hr/year). HT was allowed to be a non-integer value, as it was assumed that if, for instance, only 1.3 trucks were needed, haulers would find another marketable use for the remaining 70% of a truck's time.

### Model Results—Scenario 1

The first scenario attempts to manage the total volume of FS produced each year in St. Elizabeth, allowing for construction of facilities at various sites. Within the next two years, it is likely that only one system will be built; nevertheless, the goal in this scenario is to provide the infrastructure to allow for the treatment of the entire volume of sludge.

It is also assumed that the cost of land was not an issue (the 12 potential treatment sites are located on land already owned by the parish government). The model objective was to minimize the net cost of treatment. The model determined that a treatment facility

**Table 1.** Scenario 1—Optimal Fecal Sludge Volume Treated at Each Site

Treatment site	Truckloads treated annually
1	145
2	38
3	98
4	61
5	11
6	65
7	101
8	140
9	114
10	60
11	61
12	141
Total treated	1,035

should be built at each of the 12 sites, with capacities as shown in Table 1, along with the purchase of 0.513 trucks. The total net cost was calculated to be J\$5,853,055.

The unit-benefit value  $S$  that would result in a net cost of  $Z=0$  [see Eqs. (1) and (2)] was calculated to be approximately J\$7,600. While this value does not represent the exact net-benefit value required to “break even,” the model might eventually be used to approximate such a value. Some citizens in Jamaica, mainly in the capital city of Kingston, already pay as much as J\$9,000 to have their systems emptied. It would, therefore, be of interest to planners that the calculated “break-even” value for hauling fees falls within the range of current fees charged island wide.

### Model Results—Scenario 2: People Affected versus Cost

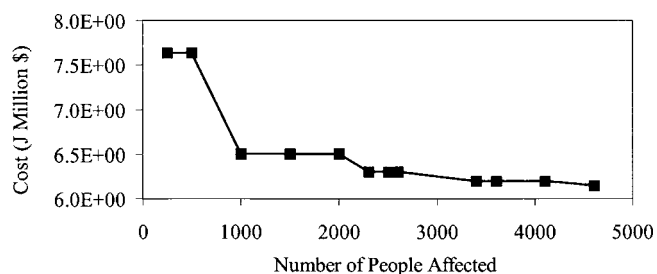
The first objective, as discussed in the previous two scenarios, was to minimize the net costs of hauling and treatment. The second objective considered here was to minimize the number of people affected in the region of treatment facility construction. The constraint method of multiobjective optimization was used to develop an optimal trade-off curve between net cost and the number of people negatively affected by the project. The affected population at each treatment site was included in the GAMS model, and the acceptable number of people was constrained as follows:

$$\sum_{j=1}^{12} N_j \times a_j \leq 250 \text{ to } 5000 \quad (7)$$

where  $N_j$ =binary decision variable (1 if facility is built at  $j$ , 0 if it is not), and  $a_j$ =number of people affected by construction of facility at  $j$ . The model was run while varying the acceptable population affected between 250 to 5,000 people. The potential number of people affected has little physical meaning with respect to the population in the surrounding areas immediately outside the 1 km radius. The optimal trade-off curve illustrated in Fig. 4 provides a first step in future discussions surrounding facility construction.

When the number of people in the vicinity of the treatment sites is limited to either 250 or 500 people, the model suggests that the construction of one large facility at treatment site 8 (YS and Ipswich, in Maggoty, St. Elizabeth) would be optimum. Due





**Fig. 4.** Optimal trade-off between cost and number of people affected

to the location of this site, 1.615 hauling trucks would be required to service the entire parish and the net present-worth cost would be approximately J\$M7.63 (or US\$M1.27).

Each of the model runs produces a unique cost and/or facility construction and, hence, hauling management plan (as shown in Table 2). The cost of treatment plans ranges from J\$M6.15 to J\$M7.63, corresponding to the purchase of 0.697 to 1.615 trucks, respectively. Treatment Sites 7, 8, and 9 appear prominently in the model output, as a result of the relatively low population density within a 1 km radius of those sites. For planners, it is interesting to note that while Site 3 required the least total hauling time, it did not appear in any of the model outputs from this second scenario that considered the number of people affected.

#### **Analysis of Model Sensitivity to Treatment Site Costs**

This section considers varying treatment site conditions since detailed physical data on each potential site were not available. The prefability analysis suggested that each of the 12 sites was suitable for facility construction; however, there may be other factors that render one or more sites less expensive than others. Land slope, for instance, appeared as though it would not pose a problem at any of the sites, but because slope estimates are only approximate, it is possible that significant fill or excavation is needed to level sites for construction resulting in added costs. Other physical site variables might include demolition, soil-type changes, and necessary site remediation.

The model considered only land parcels already owned by the parish council as potential treatment sites. In the event that land was purchased in other regions of St. Elizabeth for treatment facility construction, cost might vary, depending on the type and location of the site. To test the model's sensitivity to cost variation

**Table 3.** Model Results Summary

Scenario	Description	Total cost (J\$)
1	Construction at various sites, without consideration of population affected	5,853,055
2a	Constrained to affect approximately 0.1% of the population of St. Elizabeth	7,636,365
2b	Constrained to affect approximately 3.1% of the population of St. Elizabeth	6,149,926

among the 12 treatment sites (in the absence of physical data), weights were added to the three preferable sites from the Scenarios 2 and 3 (Sites 7, 8, and 9). Weights of 1.2, 1.5, and 2 were added to Sites 7, 8, and 9, respectively, in order to test the model's sensitivity to variable treatment site costs. The cost increased from the second scenario (J\$5,853,035) to J\$6,135,491, including 0.654 trucks. The increase in cost at three preferable sites resulted in an increase in net cost of approximately J\$282,456, or 4.8% of the original overall cost. The resulting management plan did not include any of the three preferable sites (7, 8, and 9); instead it suggested construction at all of the remaining nine treatment sites.

#### **Analysis of Results**

The results from each of the scenarios are summarized in Table 3, and those results, combined with the sensitivity analysis, should enable useful future discussions of sludge management. In addition, it is useful to consider what supplemental information would be necessary to enhance the model and to address a wider array of management and planning questions than was addressed with this preliminary model.

#### **Potential Improvements to Scenario 1: Allowing for Construction at Various Sites**

In the first scenario, costs corresponding to hauling, hauling truck, operator salary, treatment facility capital, operation, and maintenance were considered by the model. The potential benefits of hauling fees and biosolid sales were also included to define net costs. The model output suggested the construction of a facility at each site and a hauling plan for sludge from each of the 308 census areas. Economies of scale were not incorporated in the

**Table 2.** Scenario 2—Model Run Results

Population affected	COST (J\$)	Trucks	Facility and volume of sludge to be treated
250	7,636,365	1.615	t8 1,035
500	7,636,365	1.615	t8 1,035
1,000	6,508,411	0.918	t7 622, t8 413
1,500	6,508,411	0.918	t7 625, t8 410
2,000	6,508,411	0.918	t7 622, t8 413
2,300	6,307,747	0.794	t7 581, t8 315, t9 139
2,500	6,307,747	0.794	t7 581, t8 315, t9 139
2,600	6,307,747	0.794	t7 581, t8 315, t9 139
3,400	6,196,919	0.726	t6 270, t7 338, t8 301, t9 126
3,600	6,196,919	0.726	t6 270, t7 338, t8 301, t9 126
4,100	6,196,919	0.726	t6 270, t7 338, t8 301, t9 126
4,600	6,149,926	0.697	t6 322, t8 314, t9 126, t11 273

model. While this is often the case with small-scale wastewater projects, the model might be improved with their incorporation. More detailed and reliable cost, operation, and maintenance values would provide a better sense of economies of scale. This, in turn, would provide a better understanding of the nature of the capital costs of treatment relative to the other costs and benefits associated with sludge management.

### ***Potential Improvements to Scenario 2: People Affected versus Cost***

Scenario 2 provided a sense of the number of people potentially affected by facility construction using an estimate of the population in the vicinity of each treatment site. The model results describe the optimal trade-off (or Pareto) curve between the number of people negatively affected and the cost of management. Nevertheless, sound and detailed information about the immediate surroundings of each of the treatment sites is still lacking. Before including any site in the model, significant time should be devoted to gaining a thorough understanding of its characteristics. As with many models that seek to quantify the social costs and benefits of engineering and planning decisions, it would be impossible to determine the "cost" of affecting each citizen of St. Elizabeth. It is, therefore, important that planners collaborate with community members surrounding potential treatment sites, and engage in a discussion of the potential detrimental affects of FS treatment facilities.

### ***Potential Improvements to Analysis of Model Sensitivity to Treatment Site Costs***

Variations in treatment site costs as well as consideration of other potential treatment sites should also be incorporated into the model. Depending on the degree of variation, the relationship between the marginal costs of treatment and those of hauling trucks will vary, changing the nature of the model and its results. If variations in construction and site-specific costs are found to be significant, they can be readily incorporated in the model structure.

## **Recommendations and Conclusions**

This study has introduced a preliminary integrated model for evaluating the optimal trade-offs among treatment costs associated with a wide range of treatment options and the number of people impacted by various fecal sludge (FS) management strategies. An integrated assessment led to the formulation and solution of the FS management problem as a mixed integer linear program. Further, the integrated assessment enabled us to clearly formulate the objectives, constraints, and decision alternatives, as well as to provide an initial evaluation of the possible optimal solutions. Development and application of the mixed integer linear programming model provided insight into the value of a systematic approach to the problem of FS management, as well as into the problems one might face in using this type of model for planning purposes. The scale of the model and a lack of detailed site data were the most significant drawbacks to the model.

The modeling approach introduced here may better serve a larger region than considered here. In the case of the St. Elizabeth region, up to two hauling trucks would be required to serve the entire population. A larger region would require more trucks and, in turn, a more rigorous calculation of travel time and routing for

sludge hauling. The size of the region allowed for the calculation of relative traveling times among the treatment sites and the census areas. In addition to model scale, development of the model suggested that this type of systematic approach to sludge management would require more reliable and detailed treatment site data and more comprehensive construction costs, in order to distinguish potential treatment sites from each other. The variable nature of the potential treatment sites should, therefore, be incorporated in the objective function.

Future analysis should include more detailed cost calculations and should possibly incorporate nonlinear cost functions into the model. Facility construction represents a significant portion of the resulting net cost; thus, a change in the cost function might result in a large change in the optimal objective function value. In future analyses of island-wide FS management in Jamaica, spent bauxite mines should also be considered potential sites for treatment facility location. Land reclamation could be added to the objective function as a potential benefit.

While a survey was conducted in order to assess the willingness to pay for hauling services, as well as existing hauling services available, additional work in the region should include more detailed social analyses of the treatment locations, the potential for selling biosolids as fertilizer, and the social aspects of construction and operating and maintenance financing of these systems.

It is our hope that with input from all parties, the model might prove to be a springboard for collaboration and the basis for discussions surrounding trade-offs, potential treatment sites, cash-flow options, capital treatment costs, and other FS sludge management issues. Further study of the region and collaboration with the aforementioned groups and individuals might provide the information necessary to render the model a working tool. In other instances and regions, where all the necessary data are readily available, the model could be used readily. Further application of this model will, therefore, require the collaboration of local businesses, citizens of St. Elizabeth, the Ministry of Health, the Parish Development Committee, and other groups and individuals dedicated to providing the services associated with sludge management.

This research appears to be the first effort to take a systematic approach to FS treatment. While FS management has historically been studied and addressed as a localized problem, there are benefits to taking a systems approach, particularly in instances such as this one, where government agencies are focused on developing guidelines and policies for management. As arguable as the assumptions and numbers herein might be, systems models, such as the one introduced here, provide structure to the discussion.

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## **References**

- ArcGIS. (2006). ESRI GIS and mapping software, (<http://www.esri.com>) (September 26, 2006).



- Bartlett, L., and Vesilind, P. A. (1998). "Expediency and human health: The regulation of environmental chromium." *Science and Engineering Ethics*, 4(2), 191–201.
- Carr, R. (2001). "Excreta-related infections and the role of sanitation in the control of transmission." World Health Organization (WHO). *Water quality: Guidelines, standards and health*, L. Fewtrell and J. Bartram, eds., IWA Publishing, London, Ch. 5.
- Center for Water Resources Studies (CWRS). (1999). "Septage management and treatment." *Final Rep.: Domestic Septage Management Review*, Dalhousie Univ., Nova Scotia Canada.
- Crohn, D. M., and Thomas, A. C. (1998). "Mixed-integer programming approach for designing land application systems at a regional scale." *J. Environ. Eng.*, 124(2), 170–177.
- Ellis, K. V., and Tang, S. L. (1991). "Wastewater treatment optimization model for developing world. I: Model development." *J. Environ. Eng.*, 117(4), 501–518.
- Heinss, U., Larmie, S. A., and Strauss, M. (1998). "Solids separation and pond systems for the treatment of fecal sludges in the tropics." *Rep. by the Swiss Federal Institute for Environmental Science (EAWAG)*, Dept. of Water and Sanitation in Developing Countries (SANDEC), Switzerland, [http://www.eawag.ch/publications\\_e/e\\_index.html](http://www.eawag.ch/publications_e/e_index.html) (February 5, 2005).
- IDRISI Software. (2006). Clark Labs, Clark Univ., <http://www.clarklabs.org/index.cfm> (September 26, 2006).
- Inform Website. (2006). [http://www.informinc.org/pr\\_ggt.php](http://www.informinc.org/pr_ggt.php) (September 26, 2006).
- Klingel, F., Montangero, A., and Strauss, M. (2001). "Nam Dinh—Planning for improved fecal sludge management and treatment presented at the Vietnam Water and Sanitation Association's yearly conference, Hanoi." [http://www.eawag.ch/publications\\_e/e\\_index.html](http://www.eawag.ch/publications_e/e_index.html) (February 5, 2005).
- Leighton, J. P., and Shoemaker, C. A. (1984). "An integer programming analysis of the regionalization of large wastewater treatment and collection systems." *Water Resour. Res.*, 20(6), 671–681.
- Mandl, C. E. (1981). "A survey of mathematical optimization models and algorithms for designing and extending irrigation and wastewater networks." *Water Resour. Res.*, 17(4), 769–775.
- McConagha, D. L., and Converse, A. O. (1973). "Design and cost allocation algorithm for waste treatment systems." *J. Water Pollut. Control Fed.*, 45(12), 2558–2566.
- Montangero, A., and Strauss, M. (2002). "Fecal sludge treatment." Swiss Federal Institute for Environmental Science (EAWAG), Department of Water and Sanitation in Developing Countries (SANDEC), [http://www.eawag.ch/publications\\_e/e\\_index.html](http://www.eawag.ch/publications_e/e_index.html) (February 5, 2005).
- Phillips, K. J., Beltrami, E. J., Carroll, T. O., and Kellogg, S. R. (1982). "Optimization of areawide wastewater management." *J. Water Pollut. Control Fed.*, 54(1), 87–93.
- Rocky Mountain Institute. (2004). "Valuing decentralized wastewater technologies: A catalog of benefits, costs, and economic analysis techniques."
- VanHoven, D. (2004). "Septage in Jamaica: An assessment of the situation and an evaluation of treatment alternatives." *Rep. for the Ministry of Health*.