Transportation Analysis for Sludge Transport Routing Design and Landfill Site Selection

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A solution framework for the sludge landfill site selection problem that arises in the context of environmental planning is presented. The problem may be defined as follows: given a set of environmentally acceptable candidate landfill sites, identify the site that minimizes a weighted combination of two objectives (system descriptors), the present worth value of the transportation operation costs and the resulting population disturbance of the chosen set of transportation routes. The solution methodology is demonstrated on data developed for the city of Phoenix, Arizona.

The sludge landfill site selection problem (SLSSP) arises in the context of an environmental planning process focusing on sludge landfill site selection. The ideal solution is to identify the suitable landfill site that minimizes a weighted combination of two objectives: the present worth of the transportation operation costs and the associated population disturbance. This paper presents a methodology to generate a best possible solution to the SLSSP on the basis of its bi-objective formulation. The mathematical formulation of the SLSSP and an overview of the sludge landfill analysis algorithm (SLA) are presented first. A demonstration application to the SLSSP for the city of Phoenix, Arizona, is then presented, and finally the results and directions for future research are provided.

Previous solution approaches to the SLSSP (*1,2*) focused on only a single objective, namely that of minimizing the annual relative cost of transporting sludge from water treatment plants (WTPs) to the candidate landfill site. Such approaches were considered inadequate because they did not account for the time value of money and did not address the major objective of minimizing population disturbances along transport routes. It is recognized that transporting sludge via residential neighborhoods is disrupting and undesirable. Thus one can formulate the SLSSP as a bi-objective problem consisting of the selection of a landfill site that minimizes a weighted combination of the present worth of the transportation operation costs and the associated total population disturbance.

$$\underset{(\text{all } i \in \text{SL})}{\text{Minimize}} \; [c_1\text{PW}_i + c_2\text{PD}_i] \tag{1}$$

where

PW_i = present worth of the transportation operation costs of transporting sludge from all WTPs to landfill site i,
PD_i = total population disturbance associated with the transportation operation of landfill site i,
c_1, c_2 = weights reflecting the relative importance of the present worth of transportation operation costs and the associated population disturbance, and
SL = set of environmentally acceptable candidate landfill sites (known a priori).

By varying c_1 and c_2 one can generate different nondominated (pareto-optimal) configurations that achieve different trade-offs between the present worth of transportation operation costs and total population disturbance. If c_1 is set equal to 0 then the SLSSP becomes one of selecting the landfill site whose total population disturbance is minimum. Alternatively if c_2 is set equal to 0 then the SLSSP becomes one of selecting the landfill site whose present worth of transportation operation costs is minimum (historically the earlier formulation of SLSSP).

PRESENT WORTH OF TRANSPORTATION OPERATION COSTS

The present worth of the transportation costs (over the landfill's design life span) associated with one candidate landfill site i (PW_i) is computed as follows:

$$\text{PW}_i = \sum_{\text{SW}} \text{PW}_{ij} = \sum_{\text{SW}} (\text{PW}_{cc} + \text{PW}_l + \text{PW}_{o,m,f})_{ij} \tag{2}$$

where

PW_{ij} = present worth of the transportation operation costs of the chosen route between WTP j and landfill site i,
PW_{cc} = present worth of the chosen route's equipment capital costs (tractor-trailer combinations),
PW_l = present worth of the chosen route's labor costs,
$\text{PW}_{o,m,f}$ = present worth of the chosen route's equipment operation, maintenance, and fuel costs, and
SW = set of all WTPs.

POPULATION DISTURBANCE

Future residential population densities were compiled by using data from the Bureau of Census projections. Data compiled for the city of Phoenix SLSSP indicate that an area's residential population density (projected for 2020) can be classified into three categories: (a) low-density areas (population densities of up to 2,000 people in a radius of 1 mi), (b) medium-density areas (population densities between 2,000 and 5,000 people), and (c) high-

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density areas (population densities in excess of 5,000 people). In addition links in outlying areas and freeway links are assumed to have zero population disturbance. The population disturbance (pd_l) of link l with length l_l is computed as follows:

$$pd_l = \frac{6{,}000}{3.14} l_{hd} + \frac{3{,}500}{3.14} l_{md} + \frac{1{,}000}{3.14} l_{ld} + 0 * l_{nd} + 0 * l_{frwy} \quad (3)$$

$$\text{subject to } l_{hd} + l_{md} + l_{ld} + l_{nd} + l_{frwy} = l_l \quad (4)$$

where

l_{hd} = length of part of link l in high-density areas,
l_{md} = length of part of link l in medium-density areas,
l_{ld} = length of part of link l in low-density areas,
l_{nd} = length of part of link l in outlying no-density (zero density) areas, and
l_{frwy} = length of part of link l in freeways.

Not all five subcomponents may be present in a given link. The value of (6,000/3.14) equals the number of disturbed people per mile of high-density link length. It is assumed that a high-density area has 6,000 people in a circle with a radius of 1 mi. Thus there are 6,000 people in an area of 3.14 mi^2, implying that (6,000/3.14) people are disturbed per 1-mi length along the link. It is assumed that a link of 1 mi in length disturbs the population in an area lying within a disturbance bandwidth of 0.5 mi on both sides of the link. This is not a limiting assumption, because the important issue is the relative ratio of the population disturbances of two landfill sites rather than their absolute values.

Every shipment of sludge from WTP j to landfill i (on the chosen route) disturbs twice the total population living along the route in every round trip. Thus the population disturbance (PD_{ij}) of the chosen route between landfill site i and WTP j is computed by multiplying twice the route's total population disturbance by its number of daily shipments (s_{ij}).

$$PD_{ij} = 2\left[\sum_{\text{all links } l\in L(i,j)} pd_l\right] * s_{ij} \quad (5)$$

where $L(i,j)$ is the set of all links on route from WTP j to landfill site i.

The system population disturbance (PD_i) associated with candidate landfill site i is computed as follows:

$$PD_i = \sum_{SW} PD_{ij} \quad (6)$$

CHOICE OF TRANSPORTATION ROUTES

There are many routes for transporting sludge from a given WTP j to a candidate landfill site i. These routes are generated with the application of the K-shortest routes algorithm without repeated nodes (*3–6*) to the transportation network. K routes are generated for each pair of candidate landfill site i and WTP j. The present worth of the transportation operation costs and the resulting route's total residential disturbance are computed for each route. The route chosen for transportation is the one that minimizes a weighted combination of both objectives of cost and population disturbance. Thus the problem can be formulated as follows.

Choose route k (among K possible routes) from WTP j to landfill site i such that ($c_1\, PW_{ij,k} + c_2\, PD_{ij,k}$) is a minimum, where $PW_{ij,k}$ and $PD_{ij,k}$ are the present worth of the transportation operation costs and population disturbance of route k, respectively. Thus the chosen route for transportation is not necessarily the shortest travel time route, because the latter's resulting total population disturbance may be quite high.

SLUDGE LANDFILL ANALYSIS ALGORITHM

SLA is an analysis algorithm that evaluates for each candidate landfill site two major descriptors, namely the present worth of the transportation operation costs and the associated population disturbance of the transportation operation. This requires the identification of the collection routes to the landfill site under evaluation from all WTPs. Thus SLA first selects the transport route from every WTP to the landfill site under evaluation. There are many such routes from a WTP to the landfill site. These routes differ in length, average running speed, travel time, link composition (some links may be part of highways, arterials, or streets), and population disturbance. The shortest-time route may require the smallest operation fleet size; however, it may have a high population disturbance. An alternate, slightly longer route (with only a small increase in the resulting transportation costs) may result in a much smaller population disturbance, hence the need to identify and consider many routes between each pair of landfill site and WTP. SLA implements a K-shortest routes algorithm without repeated nodes (loopless) to generate K routes in increasing order of round-trip travel time (the selection of K's value is discussed below). SLA then determines for each such route the number of daily shipments, the required fleet size, the resulting present worth of transportation operation costs, and the route's population disturbance. On the basis of two descriptors of each route a decision is made to select the transportation route that minimizes a weighted combination of both descriptors.

The same process is then repeated (with the same site under evaluation) for every one of the remaining WTPs (inner DO loop). Again the K-shortest routes algorithm is implemented to determine K possible routes between the candidate landfill site and each WTP. On the basis of each possible route's two descriptors, the transportation route is selected and the resulting route's present worth of the transportation operation costs and population disturbance is determined. The landfill site's system descriptors are then obtained by aggregating the present worth of the transportation operation costs for the chosen routes and their corresponding population disturbances. The whole procedure is then repeated for each candidate landfill site (outer DO loop). Once the two descriptors of each candidate landfill site are determined, the set of nondominated candidate landfill sites is generated. SLA has been described previously (*7*).

The input to SLA can be classified into four categories: transportation network data, population disturbance data, operational characteristics data, and present worth analysis data. The output of SLA can be classified into three categories: route properties, landfill sites' system properties, and the set of nondominated candidate sites. The different cost components are computed by SLA as follows.

Number of Daily Shipments Between Landfill Site i and WTP j

The number of daily shipments (s_{ij}) depends on the WTP j monthly tonnage of sludge production (M_j), the sludge density

(21 lb/ft^3), and the dry sludge capacity of a typical truck-trailer combination (5.67 tons of dry solids). s_{ij} is given by

$$s_{ij} = \left\lceil \frac{12 * M_j}{5.67 * YDO} \right\rceil \quad (7)$$

where [x] is the smallest integer greater than or equal to x, and YDO is yearly days of operation (assumed to be 260 days/year).

Maximum Number of Round-Trips by One Truck on Each Route

The maximum number of round-trips by one truck on each route (q_{ij}) is dependent on the route's round-trip travel time and the duration of the daily collection operation. The round-trip travel time (RTT_{ij}) to landfill i from WTP_j is the sum of twice the travel time between WTP_j and landfill site i, the loading time at WTP_j, and the unloading time at landfill site i. q_{ij} is given by

$$q_{ij} = \left\lfloor \frac{DHO * 60 \text{ min/hr}}{RTT_{ij}} \right\rfloor \quad (8)$$

where [x] is the smallest integer less than or equal to x, and DHO is daily hours of operation.

$$RTT_{ij} = 2\left[\sum_{\text{all links } l \in L(i,j)} tt_l \right] + (t_u)_i + (t_l)_j \quad (9)$$

where

tt_l = one-way travel time of link l,
$(t_u)_i$ = unloading time at landfill site i (assumed to be 15 min),
$(t_l)_j$ = loading time at WTP j (assumed to be 30 min), and
$L(i,j)$ = set of all links on route from j to i.

Fleet Size on Each Route

The fleet size on each route, $(N_t)_{ij}$, necessary to transport sludge to landfill i from WTP j is based on the maximum number of round-trips by one truck on each route, the monthly tonnage of dry solids produced at WTP j, and the dry solids capacity of truck-trailer combinations. $(N_t)_{ij}$ is given by

$$(N_t)_{ij} = \left\lceil \frac{12 * M_j}{5.67 * YDO * q_{ij}} \right\rceil \quad (10)$$

ILLUSTRATIVE APPLICATION FOR CITY OF PHOENIX

The following assumptions were made for the city of Phoenix SLSSP:

1. Landfill life span (n) = 50 years.
2. Truck capital cost ($Truck_{cc}$) = \$80,000.
3. Trailer capital cost ($Trailer_{cc}$) = \$45,000.
4. Annual cost escalation rate (esc) = 5 percent.
5. Annual interest rate (int) = 8 percent.
6. Life span of truck and trailer = 10 years.
7. Salvage value of truck and trailer = \$0.
8. Operation, maintenance, and fuel cost (C_{mile}) = \$0.90/mi.
9. Yearly truck labor cost (YTLC) = \$32,000/truck/year.
10. SL = 16 candidate landfill sites.
11. SW = 7 WTPs.

The K-shortest routes algorithm was adequately implemented with a K value of 100. A decision process is applied to select the route of transportation for a given pair of landfill site i and WTP j [details have been presented previously (7).]. The output of the SLA consists of the following elements.

Route Properties

Table 1 shows the first five routes of 100 shortest-travel-time routes generated from landfill site at node 11 to WTP 2 sorted in increasing order of round-trip travel time. The shortest travel time route (route 1 with a round-trip travel time of 70.8 min) itself has the least present worth value (\$1.65 million) and its population disturbance is 4,299. The cap cost corresponding to a 3 percent margin in excess of the minimum is equal to \$1.70 million. Among the remaining 99 routes, SLA searches for a route whose present worth does not exceed \$1.70 million and whose population disturbance is the minimum and under 4,299. There is not such a route; thus, route 1 is the chosen transport route and its descriptors are shown in Figure 1.

Landfill Site at Node 11 System Descriptors

Table 1(b) shows the properties of the chosen routes between the candidate landfill site at node 11 and each of the seven WTPs (only one is shown for brevity). In addition the system descriptors of the landfill site at node 11 are shown at the end of Table 1(b).

TABLE 1 Route Generation in SLA: Shortest Travel Time Routes Between Landfill Site at Node 11 and WTP 2

k-	O-	D-	Nt-	RTT-	PW(m\$)-	PD	-->	Nodal Composition of Route								
1	11	2	1	70.8	1.6480	4299	-->	11	63	64	65	68	2			
2	11	2	1	80.5	1.7151	6131	-->	11	63	64	65	68	70	69	2	
3	11	2	1	95.2	1.7738	28184	-->	11	63	76	77	13	68	2		
4	11	2	1	95.9	1.8030	17197	-->	11	63	64	65	125	126	127	2	
5	11	2	1	96.5	1.7797	11942	-->	11	63	76	77	64	65	68	2	

k = order of route, O = origin node, D = destination node, N_t = number of trucks on route, RTT = round trip travel time in minutes, PW = present worth of route, PD = population disturbance of route

From landfill site at node 11 to WTP 1:
The Chosen route corresponds to k = 2
Route is : 11 63 64 77 1
Total distance in miles = 6.51
RTT of this route in minutes = 70.36
Population disturbance = 3224
Number of daily shipments on route = 1.00
Maximum number of round trips by 1 truck = 6.00
Number of trucks needed = 1
Present worth of Capital costs = $ 0.5231 M
Present worth of O, M, & F costs = $ 0.0806 M
Present worth of Labor costs = $ 0.8462 M
Present worth of Total costs = $ 1.4499 M

---*****---SYSTEM PROPERTIES OF LANDFILL SITE AT NODE 11---*****---

The present worth of Capital costs of Landfill Site at node 11 = $ 4.0467 M
The present worth of O, M, & F costs of Landfill Site at node 11 = $ 3.6333 M
The present worth of Labor costs of Landfill Site at node 11 = $ 6.7693 M
The present worth of Total costs of Landfill Site at node 11 = $ 14.4493 M
The population disturbances of Landfill Site at node 11 = 110869

FIGURE 1 Route generation in SLA: properties of chosen routes between landfill site at Node 11 and WTPs.

The two system descriptors are the summation of the seven chosen routes' population disturbances and present worth values of transportation operation costs.

Set of Nondominated Candidate Landfill Sites

Table 2 shows the two system descriptors of the 16 candidate landfill sites. All landfill sites required 8 tractors and 15 trailers; thus, all sites had the same present worth of capital costs ($4.05 million) and labor costs ($6.77 million). The difference in total present worth of transportation operation costs results from the annual operation, maintenance, and fuel costs. The present worth of the transportation operation costs versus the associated population disturbances of 16 candidate landfill sites is shown in Figure 2. The plot shows that 4 candidate landfill sites (those at nodes 11, 12, 13, and 16) dominate the remaining 12 candidate sites. The landfill site at node 16 dominates the six sites at nodes 10, 15, 20, 21, 22, and 26 (less the present worth for the same population disturbance). The landfill sites at nodes 12 and 13 dominate the five landfill sites at nodes 8, 9, 14, 18, and 19 (less population disturbance and less present value). The landfill site at node 11 dominates the site at node 17 (less population disturbance and less present value). Thus the set of nondominated candidate landfill sites consists of four sites at nodes 11, 12, 13, and 16. Final selection from the set of nondominated sites depends on the trade-off between the present worth value and the population disturbance. If preference is given only to present worth, then the landfill site at node 13 is the final selection. Alternatively if preference is given only to population disturbance, then the landfill site at node 16 is the site of choice. Any case other than the two boundary conditions requires the specification of the trade-off between present worth and population disturbance.

SUMMARY AND CONCLUSIONS

This paper presents a solution methodology to the SLSSP that recognizes, in addition to the cost minimization objective, a second objective in which the population disturbance associated with the transportation network is minimized. The solution methodology relies on an SLA to select the landfill site. All environmentally acceptable candidate landfill sites are analyzed through this algorithm, which identifies *K*-shortest travel time routes of transportation between one landfill site and each of the WTPs. On the basis of a prespecified trade-off between the optimization objectives, SLA selects the routes of transportation and then evaluates the two system descriptors of each landfill site, namely the present worth of the transportation operation costs and the resulting population disturbance of the associated set of transportation routes.

TABLE 2 System Descriptors of 16 Candidate Landfill Sites*

Landfill Site at node number	PW capital	PW labor	PW o,m,&f **	PW total	Pop. Dist
8	4.0467	6.7693	5.7214	16.5374	357535
9	4.0467	6.7693	4.1895	15.0055	163858
10	4.0467	6.7693	5.4679	16.2839	104261
11	4.0467	6.7693	3.6333	14.4493	110869
12	4.0467	6.7693	3.3753	14.1913	137978
13	4.0467	6.7693	3.3498	14.1658	162503
14	4.0467	6.7693	4.1219	14.9379	194390
15	4.0467	6.7693	5.3100	16.1260	104261
16	4.0467	6.7693	4.8410	15.6570	104261
17	4.0467	6.7693	3.9782	14.7942	131768
18	4.0467	6.7693	4.3126	15.1286	200523
19	4.0467	6.7693	4.5249	15.3409	174243
20	4.0467	6.7693	5.5912	16.4072	104261
21	4.0467	6.7693	5.3093	16.1253	104261
22	4.0467	6.7693	6.0129	16.8289	104261
26	4.0467	6.7693	6.2942	17.1102	104261

*) All present worth values are in millions of dollars
**) Operation, maintenance, and fuel costs

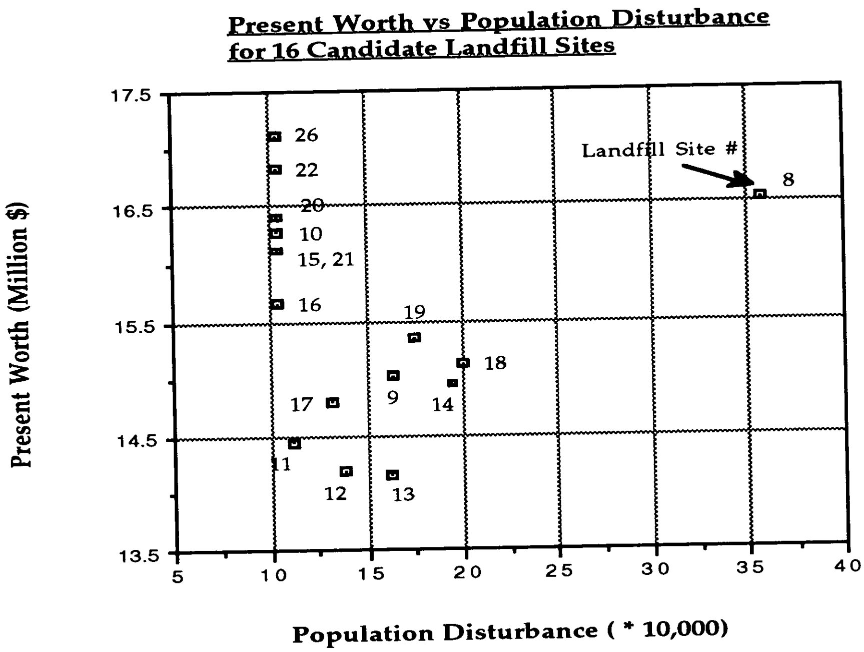

FIGURE 2 Present worth versus population disturbance of 16 landfill sites.

The testing of the solution framework on data generated for Phoenix, Arizona, revealed the adequacy of the solution.

The proposed solution approach modeled the transportation operation between a landfill and each WTP as a single origin-single destination system. Each WTP had its own independent fleet size that transported sludge from that WTP only to the candidate landfill site. This assumption increases in validity as the fleet size associated with each WTP becomes larger and operates with a higher frequency of daily shipments. The test application to Phoenix indicated that the fleet size associated with each WTP consisted mostly of one truck conducting one daily round-trip operation. This may encourage the pooling of resources among WTPs and changes the nature of the transportation operation to that of multiple origins-single destination. As a result the system's present worth of transportation operation associated with each site is reduced. For future research the solution framework may be modified to accommodate the above situation.

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