22 Optimum location of liquid waste disposal facilities: formation fluid in the Petrolia, Ontario, oilfield

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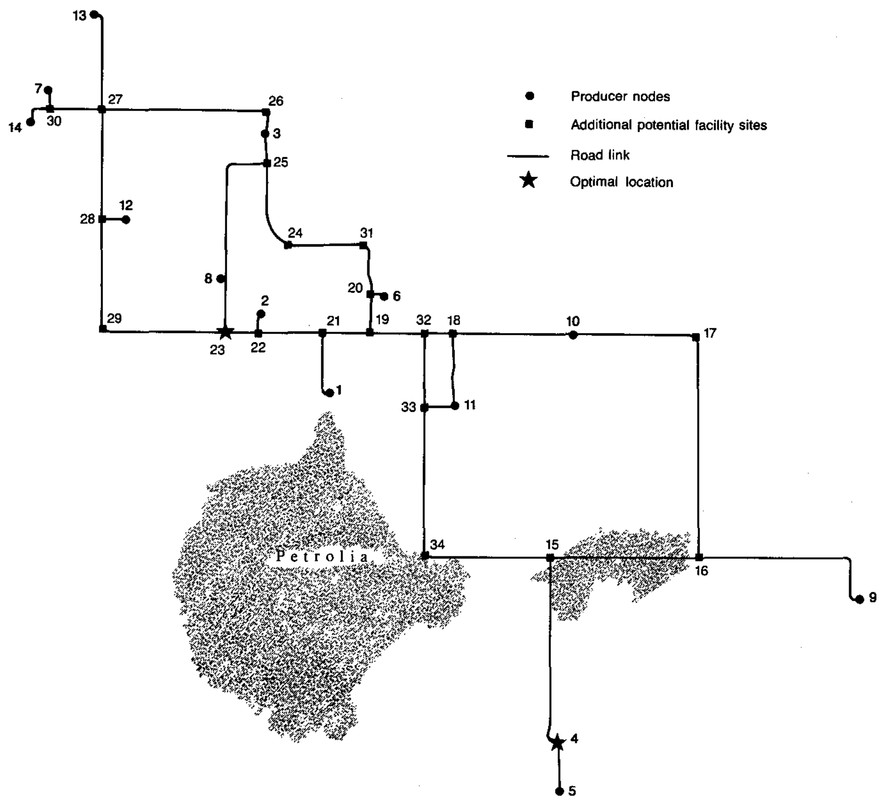
1. BACKGROUND

The Petrolia field in Southwestern Ontario was one of the first commercial oilfields in the world, and has been in continuous production for some 125 years. Despite this, it is estimated that no more than 20% of the oil has been extracted so far, and that production at current rates and using current methods will be possible well into the next century. However, the extraction technique used in the field results in the generation of a large quantity of waste fluid, which has traditionally been disposed of by evaporation or by discharge into surface watercourses. This practice is increasingly regarded as undesirable because of associated air and water pollution.

The field is small in extent and shallow, with the oil bearing formation being no more than 160m below ground level. It is, therefore, well suited to the kinds of small scale production methods which have been used in the area since the last century. In 1984 there were fourteen active producers located within a 5 km. radius of the centre of the town of Petrolia. The field is roughly elliptical in shape with the major axis running to the northwest and southeast of the town (Figure 1.1).

Typically, successful Petrolia producers operate and maintain up to thirty wells, each of which if pumped continuously will yield, on average, about a barrel of oil per day. The typical annual production from 30 wells is about 500 m^3, which at the prices prevalent through 1985 provided a reasonable net income. Total production more than doubled in the period 1975-1984, primarily in response to high prices; during this period old wells were rehabilitated and a number of new wells were drilled.

Figure 1.1 Producers, roads and potential disposal sites in the Petrolia field.



The oil is pumped to the surface in the form of a weak suspension consisting of from 1% to 10% oil in an aqueous liquid variously referred to as brine or formation fluid. The percentage of oil in the output of any given well has been declining over time. However, the oil-water suspension varies in content from producer to producer and from well to well.

At the surface the oily suspension is piped to the producer's central holding system, often a wood-lined tank set in the ground, where the oil and fluid are allowed to separate by gravity. The oil is then held until it is collected by a truck and transported to a refinery in Sarnia, Ontario. The separation is almost complete, the oil shipped being roughly 99% pure, although this figure is subject to seasonal variation.

The residual fluid is a dilute brine of specific gravity approximately 1.02, about one third as salty as sea water, with a sulphurous odour. It is reputed to be readily drunk by cattle in dry weather.

The fluid may also contain small amounts of residual hydrocarbons, particularly heavy paraffin wax fractions. However although the term 'brine' will be used in this paper, it must be emphasized that the fluid is not a saturated solution of sodium chloride. All of the characteristics of the fluid vary considerably from well to well, often over very short distances. Particularly variable is the ratio of fluid to recovered oil, which also depends to some extent on the rate at which the well is pumped. Ratios vary from a low of 8:1 to a high of more than 100:1 in some wells, according to the producers, but no systematic measurement program has ever been undertaken.

By the late 1970s studies by the Ontario Ministry of the Environment had indicated that some environmentally acceptable method of brine disposal would have to be found because of continuing problems with both air and surface water quality in the Petrolia area. However it was recognized that producers in the field would likely have a limited capacity to support more costly disposal options. So the Ministry, together with representatives of the producers, undertook to examine alternative methods of disposal and their costs.

At least four disposal and treatment technologies have been discussed and evaluated in the decade or so since the problem first became an issue in Petrolia. For example, salt can be removed by reverse osmosis, but this technology is untested in this context and is likely to be very expensive. Aeration of the fluid before discharge could reduce the sulphur odour by oxidation, but would not affect the salt content. Brine could be pumped into unlined settling ponds excavated in the clay subsoil. However, this option is not entirely satisfactory because of odours, potential leakage to groundwater and the difficulty of controlling discharge during wet periods. Modification of well designs might reduce brine production rates, but experiments along these lines have not been successful. The consensus of government and producer representatives is that the only economically viable and environmentally acceptable method of disposal is by injection into a suitable formation above or below the producing layer.

In the Petrolia area, the most suitable geological layer for disposal of these waste fluids is the Detroit River formation, which lies below the oil producing zone. An intensive hydrogeological study of the environmental implications of disposal of brine to this zone was made for the Ministry of the Environment in 1984. It was concluded that long-term disposal of oil-well brine is technically feasible and environmentally acceptable in the amounts currently being generated in Petrolia.

Properly designed injection wells are likely to require a high level of capital investment. However, a single well could have the capacity to dispose of fluids generated by many producers, thereby capturing economies of scale. It seems likely, then, that the least-cost disposal option would be one or more central facilities. To test this hypothesis, a procedure was required to determine the number of disposal wells, their locations and the associated transport systems that would be least-cost under varying exogenous economic conditions.

An appropriate location-allocation model is described in the next section. The parameters used in the model are specified, along with the particular values used to find a least-cost solution for the Petrolia field under the economic conditions prevailing in 1984. The key solution algorithms were implemented in the form of a series of programs for the IBM PC and compatible systems. The final sections of the paper discuss some of the issues involved in implementation of the solution.

2. LOCATION ALLOCATION MODEL

Location allocation models are designed to determine optimum solutions to problems in which one or more central facilities must serve a spatially dispersed demand (for a comprehensive review see Handler and Mirchandani 1979). They vary in application from social services such as fire stations and schools to retail stores, warehouses and factories. In this case the facilities are central disposal wells, the service is brine disposal, and the demand is generated by the producers at the existing separators. We propose to structure the model so as to determine the optimum number, size and locations of facilities, the pattern of allocations of demand to facilities, and the optimum method of transport. All elements in the model will be reduced to economic terms, and the optimum solution will be defined as the one with least cost incurred to the system as a whole.

We assume that the space in which the model will be constructed is discrete; in other words, the set of all possible places in the study area is finite, of size n. The presence of a producer of brine at a place j is indicated by a positive production w_j per unit of time. To limit the complexity of the search for an optimum solution, only some of the set of places are considered candidates for the location of a facility; a node i is a candidate if $c_i=1$, else $c_i=0$. In practice, the set of places can be limited to the union of the set of producers and the set of candidate nodes.

The allocation of brine from producers to disposal facilities is denoted by the matrix $\underline{x}$; $x_{ij}=1$ if brine from a producer at node j is transported to node i for disposal, else $x_{ij}=0$. The cost of transporting one unit of brine by the cheapest available mode is given by d_{ij}, so the total transport cost for one unit of time is:

$$\sum_i \sum_j x_{ij} \, d_{ij} \, w_j \qquad (1)$$

The elements of the matrix $\underline{x}$ must be constrained to ensure that all brine is disposed of:

$$\sum_i x_{ij} = 1 \quad \text{if } w_j \neq 0 \qquad (2)$$

and that allocations are made only to candidate nodes with open facilities:

$$x_{ij} \leqslant x_{ii} \leqslant c_i \text{ for all } i,j \qquad (3)$$

Finally, we assume that each producer transports all brine to one facility:

$$x_{ij} = \{0,1\} \text{ for all } i,j \qquad (4)$$

The number of facilities, p, will be equal to the trace of the $\underline{x}$ matrix, and the objective will be to minimize the sum of the transport and facility construction and operating costs.

In this particular implementation of the generic model, the production rates and transport costs are known, and the task is to determine the optimum allocation matrix $\underline{x}$, which will indicate the optimum pattern of transport, and the number and locations of the facilities. The literature refers to this as a plant location (Efroymson and Ray 1966) or warehouse location (Feldman, Leherer and Ray 1966) model. In our implementation, the number of brine disposal facilities p is determined by successively optimizing for a range of possible p values and selecting the least cost result. Thus, we impose the additional constraint in the solution process:

$$\sum_{i} x_{ii} = p^{*} \qquad (5)$$

where p* is a possible value of p.

3. MODEL FORMULATION

A brine disposal well in the Petrolia area must be drilled to between 200 and 250 m. in order to reach the Detroit River formation. The well is then cased to below the oil-producing zone. Special features must also be incorporated into the design to prevent corrosion, since exposure to the atmosphere is likely to make the sulphurous fluid highly corrosive. The capital cost of drilling such a well and finishing it for use is estimated at between $40,000 and $50,000 at 1985 prices (all monetary amounts in this paper are expressed in 1985 Canadian dollars), well above the cost of an oil production well. It is possible for some operators to reduce these capital costs substantially by reuse of materials, sharing of equipment, etc. Many of them are experts in such techniques, having survived the period of extremely low oil prices prior to the OPEC price increases of 1973-74. However, for the purposes of this study the cost estimates used include all labour and use of land and equipment.

Unfortunately, it is not possible to assume with any certainty that a well drilled for disposal purposes will be successful since the permeability of the Detroit River formation is highly variable over short distances. It is estimated that in the Petrolia area the probability that a well drilled for brine disposal will be capable of accepting the desired flow of brine under the conditions imposed by regulatory agencies is only 80% (some estimates run as low as 60%). Brine must be injected at atmospheric pressure, and the process must not raise the fluid level in the well above prescribed limits. Any realistic costing of a disposal well must therefore include the possibility that more than one well will have to be drilled.

However, it is possible to minimize the cost of failure through careful design of the disposal well. For example, under the right circumstances a failed well can be converted to oil production, and if abandonment is necessary, the cost of casing and finishing the well need not be incurred fully. For these reasons the figure of $60,000 is taken as a reasonable estimate of the total capital or installation cost of a successful disposal well. This cost does not include any associated separation, retention or aeration systems.

Two methods of transporting brine to central disposal wells seem to be technically feasible. It would be possible to lay permanent piping from each producer's separator, and to move the brine by pumping. It would be necessary to bury the pipe for winter operation, since the freezing point of the fluid is close to that of water, and it is possible that long term use would result in clogging by residual hydrocarbons. The useful life of suitable pumps is also unclear since this form of transport is essentially untried. The other alternative is trucking. If this transport mode were adopted, it would be necessary to install insulated holding capacity at each production site to allow for winter operation.

Each of the issues discussed above has been incorporated in the particular location allocation model adapted for this study. Simplifying assumptions have been made at several points. However the model represents the best information available, and can be extended and modified as certain aspects of the problem become better understood.

The piping option is characterized by three parameters:

		Default value
A	Cost of laying pipe, $/m.	30
B	Expected life of pipe, yrs.	10
C	Pump cost, $/yr. per producer	2000

The 'default' values shown are those used for the Petrolia study. The 'expected life' parameter is intended to represent both amortization and equipment life, and is the time period used to reduce initial capital cost to cost per year, commensurate with operating cost. Since the pipe is assumed to be adequate to carry the producer's brine, the cost of this option to the producer per year is given by:

$$C_1 = AD_0/B + C \qquad (6)$$

The trucking option requires seven parameters as follows:

		Default
D	Holding capacity cost, $\$/m^3$	100
E	Maximum holding period, days	7
F	Expected life of holding capacity, yrs.	10
G	Truck load, m^3	13
H	Time to load and unload truck, hrs.	1
P	Truck average speed in motion, km./hr.	25
Q	Truck operating cost, $/hr.	37

The annual cost of the trucking mode, given a producer volume of V_0 per year, is therefore:

$$C_2 = EDV_0/365F + QV_0(H + D_0/1000P)/G \quad (7)$$

Piping thus has a fixed cost (the cost of pumping) plus a linear dependence on distance, but is substantially independent of volume, whereas trucking has a nonlinear dependence on both distance and volume. The result is that trucking is optimal or least-cost for small volumes and piping is more economical for large; however, the volume at which the optimum mode changes depends on distance in a complex way. It is possible to compute the break volume by equating the two expressions above and solving for V_0, to obtain:

$$V_0 = (C + AD_0/B)/(ED/365F + QH/G + QD_0/1000PG) \quad (8)$$

As distance tends to zero the break volume tends to:

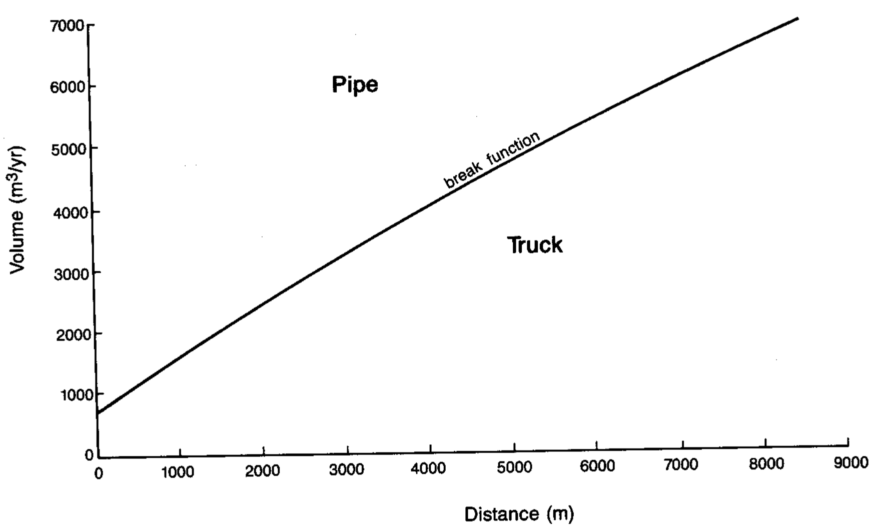
$$V_0 = C/(ED/365F + QH/G) \quad (9)$$

while at large distances the break volume is asymptotic to a limit given by:

$$V_0 = 1000APG/BQ \quad (10)$$

Figure 3.1 shows the break volume as a function of distance for the values of the parameters used in the study.

Figure 3.1 Optimum brine transport mode as a function of volume and distance for the default parameter values.



The transport cost d_{ij} in the location allocation model is then simply the lesser of C_1 and C_2 for the producer at i's volume and distance from a potential facility at place j.

The disposal facilities are characterized by a further four parameters, as follows, giving the model a total of 14:

		Default
R	Cost of completed well, $	60000
S	Expected life of well, yrs.	4
T	Capacity of well, m^3/day	300
U	Brine/oil ratio, assumed constant for the field	20

4. SOLUTION PROCEDURES

The 14 oil producer locations were designated as the first 14 places or nodes in the model. Possible connections between places were limited to existing roads, either public or private, and built up sections of Petrolia were excluded as far as possible. The intersections of this network were designated as additional nodes, or potential locations for disposal facilities, as well as a number of other suitable candidate places, giving a total of 34 nodes. Road connections between nodes were identified as links; because the network is fully connected, it is possible to find a path along the links to connect any pair of nodes. The nodes and associated links are shown on Figure 1.1.

The solution process involved five steps, each corresponding to a module in the IBM PC implementation, and written in a mixture of interpreted and compiled BASIC. The five steps are as follows:

1. Shortest path algorithm. This module takes the node production volumes and link lengths and finds the lengths of the shortest routes between all producers of brine and candidate facility locations. It is described as SPA2 in Goodchild and Noronha (1983).

2. Parameter input and editing. This module allows the user to change the values of the 14 parameters described above.

3. Transport analysis. This module takes the values of the model parameters and allows the user to examine various features of the transport cost functions for the two modes. It will also convert an input distance file from module 1 to an output file of transport costs evaluated by the cheaper mode in each case.

4. Optimization. This module identifies the optimum arrangement of facilities in order to minimize the sum of transport and facility costs, for a given number of facilities. It is a heavily modified version of the ALLOC module described by Goodchild and Noronha (1983). The basic algorithm is a vertex substitution initially described by Teitz and Bart (1968). In addition the user can search for the optimum addition or deletion of a facility, allowing the number of facilities to be changed.

5. Evaluation. The last module allows the user to obtain various statistics on a given arrangement of facilities, either the optimum or some alternative. It is a heavily modified version of the EVAL module described by Goodchild and Noronha (1983).

5. RESULTS

The values of the parameters shown earlier suggest that two wells would be optimum for the current brine production if appropriately placed. Because of the distribution of production within the study area and the geometry of the network, in which large cost penalties are incurred in moving brine around the built-up parts of Petrolia, the optimal locations are in the northwest and southeast. The northwest facility must accommodate four times as much brine as the southeast well. The optimum locations are shown in Figure 1.1.

The facility in the southeast must handle a total of 21,827 m^3/yr of brine from three producers. In all three cases the cheapest transport mode, at current production levels and assuming a 20:1 brine/oil ratio, is to install piping. The highest costs incurred by any of these producers would be $1.12 per m^3. The northwest facility must handle 103,064 m^3/yr of brine from the remaining eleven producers. Two of these, both small and remote, will find it cheaper to truck than to install pipe. The highest costs per unit of brine are incurred by one of this pair, at $3.33 per m^3.

Of the total of 124,892 m^3/yr of brine production, only 2,595 would be trucked in the optimal solution. The total transport cost of the system would amount to $79,619 per year, or an average of $0.64 per m^3. Adding facility costs brings the total annual expenditure for the entire centralized disposal operation to $109,619. However the transport component of the disposal cost is not uniformly distributed over the producers; the hightest cost is five times the average. Higher transport costs tend, of course, to accrue to the smaller, more peripheral producers, who may also have higher production costs for geological reasons.

6. IMPLEMENTATION

Several of the assumptions and parameter values used in obtaining these results can be questioned, but it is a simple matter to rerun the model under new conditions. Cost estimates associated with trucking were obtained as informal quotations from a major trucking company in the area, and are likely to be accurate. On the other hand, piping is an untested technology, so that parameter values for costs and durability are much more uncertain and consequently estimates for piping are less reliable. Moreover the assumption of a linear cost function fails to take into account the possibility that producers might share pipe facilities over at least part of the distance. Finally, it is not at all clear that brine can be piped over long distances for long periods of time without clogging of pipes and pumps.

There are also issues of administration. There is as yet no experience in the Petrolia field of operating shared disposal facilities, and it is possible that the idea may not earn immediate acceptance by producers. It may be necessary for the operator of a disposal well facility to install additional wells or brine storage tanks to ensure that there will be no interruptions of service if there are breakdowns or maintenance shutdowns. Nor does the model address the issue of who will operate the disposal service. If disposal wells are operated by producers it may be necessary to devise some appropriate method for reimbursement for service. On the other hand disposal wells might be operated by a government agency. In addition, it will be necessary to address the question of easements for pipes.

Finally, by optimizing costs over the entire system the model fails to deal with the issue of the individual producer's response. First, small peripheral producers are likely to be faced with above average charges for service and may be forced out of production. Second, a producer may estimate that the costs of installing and operating private facilities are less than the proposed charges for central disposal.

In the short term, then, the appropriate strategy would appear to be to initiate a partial test of the technology and approach, and of suitable administrative arrangements, using one of the optimal locations. If successful, this could lead in the longer term to a full system.

7. CONCLUDING REMARKS

The paper has described an application of location allocation techniques to a somewhat unique liquid waste disposal problem. Although the central vertex substitution algorithm is well known, a number of features of this particular application are novel, including the complexity of two transport modes, one of which is nonlinear in distance, and the use of add and drop heuristics in addition to vertex substitution. Both of these are likely to reduce the efficiency of the optimization and increase the probability of detecting local optima. However the problem is relatively small and the user can easily test for the effects of varying the starting solution.

The operational model was structured as an interactive package for the PC so as to allow for continuing dialogue between the parties concerned as implementation proceeded. For example, it is likely, given the recent declines in oil prices, that both production levels and the set of active producers will change before any plan can be implemented fully. But with an interactive and highly mobile package it is relatively easy to examine the effects of such changes on the optimality of the solution. For the same reason it would be useful if the analysis could be conducted graphically, but this is not currently implemented.

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