A geoenvironmental application of an optimisation model

Application d'un modèle d'optimisation à un problème geoenvironnemental

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ABSTRACT: A network of monitoring wells was installed in and around a refinery in mid 1990s as part of a research project aiming to investigate the impact of local groundwater on corrosion of buried foundations and underground storage facilities. Oil contaminated groundwater was evident in some of the monitoring wells. A second research project was started in 2000 to delineate the extent of the oil contamination mound(s) beneath the refinery and devise appropriate remedial measures. Of 30 initial monitoring wells, 15 were found operational inside the refinery in 2000. An optimisation technique is presented herein which assisted with augmentation of the monitoring network, thereby the cost-effective delineation of the oil mounds beneath the refinery. The Maximal Covering Location Problem (MCLP) was adapted and utilised to find the optimum number and locations of additional monitoring wells. The contamination results obtained from the augmented and optimised network of monitoring wells were analysed using a geostatistical tool and the oil contamination hot spots beneath the refinery were delineated cost-effectively.

RÉSUMÉ : Au milieu des années 1990, un réseau de puits de surveillance a été installé à l'intérieur et autour d'une raffinerie de pétrole pour étudier l'action des eaux souterraines sur la corrosion des fondations enterrées et des structures de stockages souterrains de la raffinerie. Une contamination par le pétrole a été détectée dans certains de ces puits. Un second projet de recherche a été lancé en 2000 pour suivre l'étendue de la contamination sous la raffinerie et concevoir des solutions appropriées pour y remédier. 15 des 30 puits fonctionnaient encore à l'intérieur de la raffinerie en 2000. Cet article présente, une technique d'optimisation du réseau de puits de surveillance afin de cartographier l'évolution de la tache de pétrole sous la raffinerie pour un coût limité. Les auteurs ont modifié le modèle d'optimisation 'Maximal Covering Location Problem' (MCLP) pour trouver le nombre optimal de puits de surveillance supplémentaires et leurs emplacements. L'analyse de ces résultats en utilisant une méthode statistique a permis de confirmer le contour de la contamination sous la raffinerie pour un coût bien défini.

KEYWORDS: Groundwater, contamination, monitoring, optimisation, MCLP, network augmentation

1 INTRODUCTION

An oil refinery constructed in the early 1970s and operated ever since caused groundwater contamination. A research project was conducted at the refinery in mid 1990s to investigate the impact of local groundwater flow on corrosion of buried foundations and underground storage facilities inside the refinery. As part of that project, a network of 30 monitoring wells was installed in and around the refinery. Oil contamination of groundwater was evident in some of the monitoring wells. A second research project was started in 2000 to delineate the extent of the oil contamination mound beneath the refinery and devise appropriate remedial solution(s). Of 30 initial monitoring wells, 15 were found to be operational inside the refinery at the beginning of the second research project. Monitoring of these wells demonstrated that free phase of oil contamination was present in groundwater at least at two separate locations inside the refinery. However, the contamination data obtained from the existing monitoring network of 15 wells were too sparse for the purpose of oil contamination delineation. Therefore, it was decided to add monitoring wells to the network within the refinery. The two major engineering challenges were identified as:

- How many monitoring wells should be added to the existing network?
- In which locations should these wells be installed?

There is substantial evidence in the literature on the application of Operations Research (OR)-based optimisation methods in different civil and environmental engineering practices (ReVelle et al. 1997). Fields of practice such as transport engineering, urban planning and water resources management are examples where successful applications of OR methods including optimisation techniques have been demonstrated. The Maximal Covering Location Problem (MCLP) is an optimisation model proposed in the literature, primarily devised to find the optimum locations for public facilities, such as ambulance dispatch centres, on a network of demand nodes (Church and ReVelle 1974). The model was modified and applied to the groundwater contamination problem in this study to assist with the cost-effective delineation of the oil contamination mound beneath the refinery.

2 MAXIMAL COVERING LOCATION PROBLEM (MCLP) – CONCEPT, THEORY AND APPLICATION

An example where the MCLP can be used for the optimum usage of the resources is the requirement to add a certain number of a public facility (e.g. ambulance dispatch centres) to an existing network in a city. The city is discretized to a set of demand nodes where additional dispatch centres can be situated. Each demand node is assigned a weight representing its population with the existing dispatch centres being attributed to the nearest nodes. From the network operator's point of view, coverage of the demand nodes (i.e. population nodes in this example) on the network is the key objective with demand nodes not being located farther than a threshold distance (i.e. maximal service distance, *S*) from an ambulance dispatch centre. In other words, a node is covered if at least one facility is located within the maximal service distance of that node. Otherwise, the node is uncovered. If a network operator instinctively places all the available resources on the nodes with the greatest nodal weight (e.g. population), the outcome will not necessarily be maximum coverage of the population by the public facilities because of the likely overlaps and gaps in the coverage of the demand nodes.

In reality, the 100% coverage target is not always achievable due to limitations in the availability of supply units. If the resources are insufficient to cover all the demand nodes, the objective changes to cover as many nodes as possible within *S* using the limited resources. Figure 1 represents a typical discretized network of demand nodes which could be considered as the potential locations for accommodating the additional facilities. With a sufficiently large maximal service distance, for example, a single facility can cover all the demand nodes on the network; hence *S* is a key decision parameter.

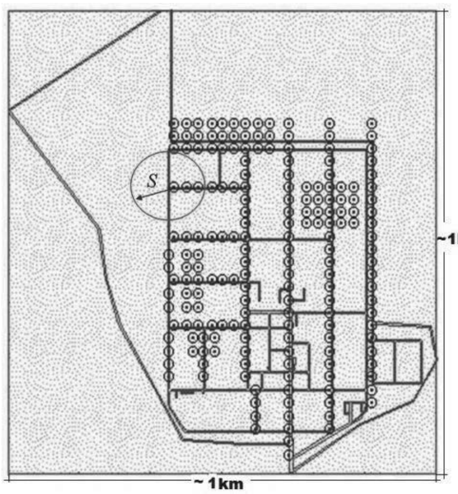

Figure 1. The concept of maximal service distance.

The MCLP is expressed as: Maximize coverage (population covered) within a desired service distance by locating a fixed number of facilities (Church and ReVelle, 1974).

The mathematical formulation of the MCLP in the context of augmentation of a groundwater monitoring network is presented in Hudak & Loaiciga (1992). Groundwater monitoring network augmentation incorporates the following stages:

- Discretize the model domain into a network of potential detection monitoring sites (nodes).
- Assign weighting to each node to quantify its relative importance for coverage by a monitoring well.
- Solve MCLP with successive values of *S* until target areal plume coverage is achieved.
- Determine the corresponding configuration of the added wells on the network.

2.1 Geometry of the grid (problem domain discretization)

An irregular grid of 188 nodes was defined within the oil refinery area taking into account the local hydrogeology as compared to similar cases where groundwater monitoring networks has been augmented, the limitations against excavation of wells on site, the spacing between the existing wells and the computational limitations for a plausible nodal weight estimation. Each of the 15 existing wells was assigned to the nearest node.

2.2 Nodal weight estimation

Due to the complex hydrogeological setting of the site and presence of a large number of potential sources of oil contamination within the refinery, using physical / numerical models to calculate the nodal concentrations (weights) was considered impractical. Kriging as a stochastic interpolator was employed instead to estimate the weights. The groundwater chemical data obtained from all 22 available monitoring wells located within and around the refinery were utilised in this nodal weight estimation.

2.3 Results

The budget allocated for additional monitoring wells included the addition of a maximum 10 number to the existing network. Therefore, the MCLP model was solved for different values of *P* from 20 to 25, noting *P* is the total number of existing and additional wells on the network and there were 15 existing wells. There were three key decision parameters; areal plume coverage which corresponds to the vertical axis on Figure 2 and is defined as the percentage of the nodes with weight values above zero covered by one or more wells (i.e. located within distance *S* of one or more wells), the total number of existing and added wells (*P*), and the maximal service distance *S* (horizontal axis on Figure 2). The marked increase in the slope of the curves on Figure 2 in two particular regions demonstrated that with a moderate increase in the value of *S*, the areal plume coverage would increase considerably compared to the other regions on the curves. If the values of *S* and the number of covered nodes (i.e. areal plume coverage) within these regions (intervals) were reasonable for decision making, then it would be possible to focus on these two regions for taking the next steps towards the final decision. The maximal service distance (*S*) plays the most important role in dictating the final configuration of the added facilities. This parameter should ideally be calculated through field, laboratory and theoretical investigations. Considering the grid size of the study area, values of *S* in the order of 100m were justified in this study.

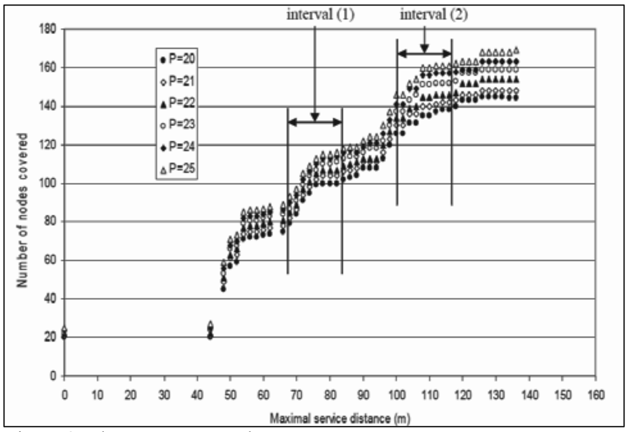

Figure 2. The coverage trend curves.

Figure 3 demonstrates that within the maximal service distance of 76m, it was possible to achieve a maximum areal plume coverage of 60% (i.e. 113 covered nodes out of total 188 nodes could be covered). This amount of coverage was not considered satisfactory. Therefore, the first interval on Figure 2 was not considered further and the second interval was selected. Figure 4 illustrates the variation of maximal service distance *S* versus *P'* (number of monitoring stations to be added). Points with unjustified values of *S* were not depicted on the graph. Figure 4 demonstrated that augmenting the network with 10 additional monitoring wells was somewhat insensitive to the magnitude of *S*, i.e. selection of 10 additional monitoring stations would result in a considerable increase in the areal plume coverage with minimum change in *S*. Hence, the network was augmented with 10 additional boreholes, corresponding to the areal plume coverage of 85% and *S*~108 m. The pattern of additional wells showed no clustering at the areas of high estimated chemical concentration (weights). This model located the additional stations (i.e. monitoring wells) at regions with high concentration of contaminant and at the same time prevented clustering of the wells (See the layout in Figures 5 and 6).

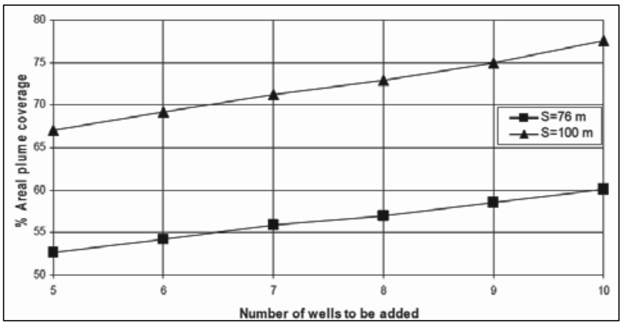

Figure 3. Cost-effectiveness curves for two distinct values of *S* derived from Figure 2.

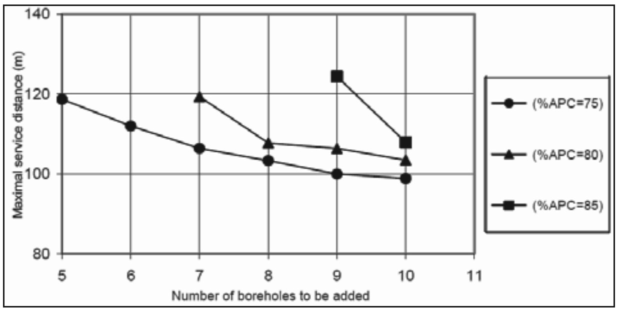

Figure 4. Variation of *maximal service distance (S)* versus the number of added wells (*P'=P-15*).

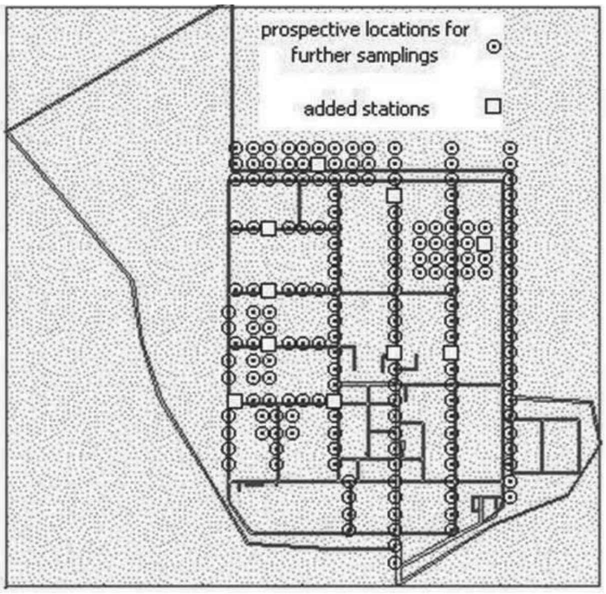

Figure 5. Added wells on the discretized network.

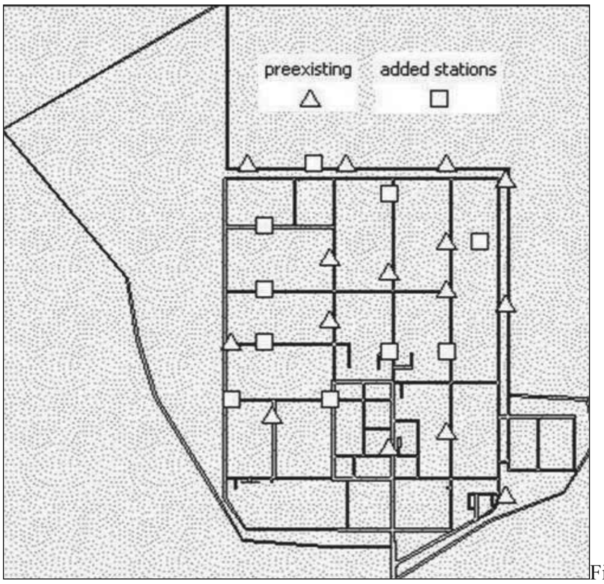

Figure 6. Added and existing wells.

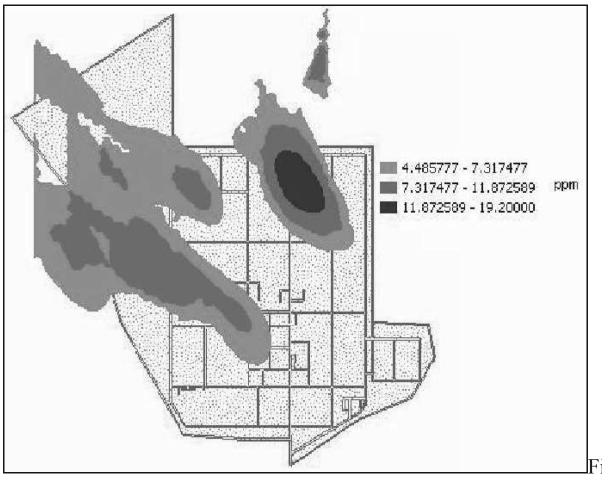

Figure 7. Hot spots of oil contamination beneath the refinery (concentrations are in terms of Total Organic Carbon).

3 GEOSTATISTICAL ANALYSES ON THE AUGMENTED DATA SET

A geostatistical analysis, using the same geostatistical tool which was used in nodal weight estimation (i.e. estimation of chemical concentrations at different nodes), was conducted on the extended data set to assist with delineating the locations and the extent of hot spots of oil contamination beneath the refinery. Three different hot spots were identified at three distinct areas. Figure 7 shows the location and the extent of the hot spots.

4 CONCLUSIONS

A geoenvironmental case history of applying an optimisation model in practice is illustrated in this paper. The Maximal Covering Location Problem (MCLP) was employed to enhance the efficiency of an existing network of monitoring wells in an oil refinery in order to assist with delineating the mounds of oil contamination beneath the refinery. After installation of the added monitoring wells at the locations predicted by the model (i.e. monitoring network augmentation), the results obtained from the augmented network demonstrated the robustness of the method. The model helped to prevent clustering of the added monitoring wells in the areas with high estimated values of the attribute (i.e. concentration) and at the same time helped to benefit the monitoring from further sampling at these areas. Using the data from the augmented network of monitoring wells and a geostatistical tool, the oil contamination hot spots were delineated cost-effectively.

5 REFERENCES

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