A LANDFILL SITE SELECTION PROCESS INCORPORATING GIS MODELLING

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SUMMARY: A selection procedure for the location of landfill sites, combining GIS technologies with site investigation methodologies, is outlined. Development of the GIS model was driven by the need to identify sites with suitable geological barriers to reduce potential risks of groundwater contamination by landfill leachate and to establish a scientific, non-biased approach to landfill site selection in order to promote public confidence in the scientific basis and overall transparency of the site selection process. There are two stages to the process: 1. GIS stage, consisting of a primary, two step screen, leading to identification of target areas, followed by a secondary screen, involving more detailed local information and site-specific analysis, to identify individual sites; 2. Geotechnical evaluation, consisting of site investigation and laboratory assessment of the geotechnical characteristics of individual sites. The developed GIS model pertains only to the primary screening. On completion of the site selection procedure, individual sites should be graded on a scale of suitability, and ranked in order of preference.

1. INTRODUCTION

One of the negative effects of increased prosperity is an escalation in the quantities of wastes produced, since it is well documented that per capita waste generation is related to economic output. Over the last two decades, waste production in the EU as a whole has increased at an average rate of 3% per annum (EEA, 2001), although over the last five years it has increased significantly more rapidly in some member states, e.g. Ireland (8%), Portugal (5%). Waste management in the EU has also undergone a major revolution over the last two decades, with a major shift towards policies of waste minimisation, recycling and reuse, whilst incineration capacity has expanded dramatically. Nevertheless, as a result of the rapid increase in waste generation, there has been little change in the overall statistics of waste disposal in the EU

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over the past two decades. Landfilling, despite being the least acceptable alternative in the waste management hierarchy, accounts for an average of 66 % of the total waste produced in the EU as a whole (EEA, 1998), so is still by far the dominant waste treatment option in the European countries. Furthermore, since landfilling continues to be the cheapest waste management option in Europe, it is likely to be the dominant method of waste disposal in the EU for the forseeable future (Allen, 2001).

Siting of landfills is a major political and environmental issue within the EU. Due to the continuing dependence on landfilling, coupled with the ongoing increase in waste generation, there will be a need for new landfill sites every few years. Also, many of the currently operating landfills are rapidly running out of space, so new landfill capacity is urgently needed. Suitable landfill sites are now at a premium in many parts of Europe, and in the light of the upsurge of the 'NIMBY (not in my backyard)' syndrome, siting of landfills has become a major political issue. The timetable involved in locating suitable landfill sites, obtaining planning permission and constructing the landfill, typically runs to several years, even if no objections are raised, which may delay completion of the planning procedure for many months or even years. Because of the above, many parts of Europe are experiencing a waste management crisis, the only solutions to which are either a significant reduction in the quantity of waste generated and consequently landfilled, or dramatic development of alternative treatment facilities.

Selection of sites suitable for landfill is a critical part of landfill systematics, but within the EU, as a result of the current policy of containment of all landfill emissions, which effectively requires the lining of all landfills, siting of landfills has been relegated to secondary importance. The assumption that any site can be engineered for landfill now commonly prevails, with the consequence that often sites unsuitable from a geological/hydrogeological standpoint are being developed, on the premise that the landfill liner gives sufficient protection to the environment (Allen, 2001). However, groundwater currently supplies a significant proportion of the potable water requirements of many European countries (e.g. Denmark 98%, Portugal 73%, Ireland, 25%), and is likely to become an even more critical resource in the future given the widespread pollution of surface waters, so location of sites with a natural geological barrier is essential.

Encapsulation of waste in a lined landfill, minimises the rate of degradation of the waste by isolating it from the natural agents of degradation, particularly rainwater - the main catalyst of degradation, (i.e. the waste is kept dry). This will have the effect of prolonging the activity of the waste and inhibiting its stabilisation to an inert state. Potentially the period of aftercare and monitoring of the landfill after closure could be prolonged for many tens or even hundreds of years (Allen, 2001), with long term, largely unpredictable, maintenance and monitoring costs. Furthermore, there is uncertainty as to the long-term durability of geomembrane liners, arising from the fact that landfill liners may be subject to severe deterioration over long time-scales due to the corrosive effects of leachate, and to the elevated temperatures generated by the exothermic processes operating within landfills (see Allen, 2001). Thus there is a real risk that degradation of the landfill liner may occur whilst the waste remains active, increasing the potential for groundwater pollution in the long term.

It is therefore imperative to seek and develop sites for landfill with natural characteristics, which can provide secondary protection to the environment in the event of failure of the landfill liner. Such sites are not uncommon, particularly in countries with thick overburden sequences, such as glacial overburden or tropical weathering profiles. Clay-rich overburden has a significant attenuation potential with respect to landfill leachate, and could be employed in conjunction with artificial liners or as a natural lining alternative to artificial liners.

GIS (Geographic Information Systems) is a useful tool that can be utilised in the search for suitable new landfill sites. GIS is a powerful technology which permits accurate processing of spatial data covering a large number of themes, from a variety of sources, specifically cartographic/numeric data, enabling processing, overlay and derivation of thematic maps, enabling tailored solutions for a whole series of applications to be furnished. Advent of highly-sophisticated computerised GIS systems, digitised map data, and Landsat satellites and other remote sensing sensors that help to define infrastuctural and land use patterns, have dramatically increased the potential of GIS to aid in the development of a more systematic approach to landfill site selection. Such an approach should ideally combine computerised GIS and geotechnical site investigation methodologies (Allen et al, 1997). There is also a need for greater transparency in the site selection procedure, in order to promote public confidence in the non-biased scientific basis of the process as a counter to the widely-encountered NIMBY syndrome.

This paper, reports on an Interreg IIC funded EU research project directed towards development of a GIS model for the location of landfill sites, conducted by a team of Irish and Portuguese engineering geologists, civil engineers and GIS experts from universities and local government (Allen *et al*, 2001). The primary objective of the project was to establish a transferable, trans-national GIS site selection framework, that could be applicable throughout the European Union, thus creating a GIS landfill model for the location of new landfill sites over the next few years. The landfill GIS model described below has been developed with the intention of providing a user-friendly tool to aid decision-making where a broad array of complex criteria must be considered, and has been designed so that non-GIS experts, but with a basic knowledge of GIS, can run the model. It should be stressed that the GIS model described here, represents only part of the landfill site selection process, being the methodology by which unsuitable sites are eliminated and suitable sites are awarded a primary grading. It should be used in conjunction with detailed engineering geology site investigation and laboratory geotechnical techniques, which are ultimately employed to rank the GIS-selected sites on a final scale of suitability.

2. THE SITE SELECTION PROCESS

Future landfill site selection procedures need to be conducted within a framework designed to achieve the following objectives

- To ensure that the most environmentally suitable site is selected, in terms of technical criteria, including impact on humans, flora, fauna, soil, water, air, climate and landscape.
- To integrate the site selection into an overall programme of regional development taking into account economic factors in siting the landfill
- To engender a public consensus on the necessity of the landfill, and a perception that the site selection process has taken account of all relevant considerations and has balanced in a fair way, all sectional interests (e.g. farming, tourism, industry, etc.)

The last objective, ultimately the greatest challenge facing local authorities and landfill operators, will only be achieved by openness and transparency in the process through a continuous programme of public consultation and dissemination of information, which should be initiated at the very beginning of the process (Begassat et al., 1995).

Parameters impacting on the suitability of landfill sites are (Allen & MacCarthy, 1991) :

- Geological - both bedrock and overburden lithology, and geological structure.
- Hydrological/Hydrogeological - infiltration and percolation rates and pathways of rainwater passing into and through the subsurface; subsurface hydrogeological features, i.e. aquifers; surface runoff characteristics.
- Topographic - height above sea level; surface slopes; exposure to the elements, particularly rain and wind.
- Ecological - effect on plant and animal habitats, biodiversity, etc.
- Climatic - local microclimate, rainfall, wind velocity etc.

- Geotechnical - foundation characteristics, side slope stability relations, site design and operation requirements; mitigation of risks.
- Social - noise; smell; dust; litter; vermin; insects; birds; visual impact; proximity to housing, domestic water wells, etc.
- Economic - distances from waste sources; road networks; site access; management costs arising from the physical characteristics of the site, etc.

In most circumstances, the first three groups of parameters will primarily control the technical suitability of sites, although, in certain circumstances, other factors may override these. For the selection process, it is necessary to establish criteria on a scale of hierarchies, with weightings assigned to the different criteria, so that in the final selection process, the various site options can be ranked objectively in order of suitability.

The overall site selection process requires a two stage approach :

- A GIS stage, which involves two primary screening steps leading to the identification of target areas for the location of landfills, and a secondary screening step in order to identify suitable individual sites, utilising output from the previous steps, and involving more detailed local information and site-specific analysis
- A geotechnical evaluation stage, involving a rigorous geological/ hydrogeological assessment of individual sites identified within the target areas, employing a combination of site investigation and laboratory techniques.

2.1 The landfill GIS model

The GIS landfill model, presented here, deals only with the two primary screening steps:

- Step 1. - exclusion of areas unsuitable for landfill
- Step 2. - weighting of residual areas

Two study areas, one in Ireland and one in Portugal were selected for the study, and GIS models were developed independently, utilising the same approach, but allowing for differences in data sets.

2.1.1. Exclusion of areas unsuitable for landfill

Exclusion areas are areas unsuitable for landfill because of the risk to the environment, the risk to human health, or excessive cost. This step of the landfill model is a non-automated phase, which requires data capture, input and manipulation by the GIS user. The data capture process aims to obtain as many digital data sets as possible; however, where digital data sets are not available, digitising may be required. In this step the data are in vector format and geo-processing techniques such as buffer and overlay are used to create the exclusion areas. Recommendations on a range of buffer distances are presented to the user to assist them in data preparation, based on a review of literature on landfill site selection (see Allen et al, 2001). The exclusion procedure essentially removes these land areas from any further consideration within the model. Exclusion criteria were divided into ‘non-geological factors’ and ‘geological and correlated factors’ (Table 1).

2.1.2. Weighting of residual areas

Residual areas are those remaining after the exclusion areas have been buffered. This land is then regarded as suitable for the location of a landfill site. However, there are still land parcels within the residual areas that may be more suitable for landfill location than others, for example areas with an underlying natural geological barrier. Thus, the residual areas need to be further examined in relation to a number of criteria. These have been divided into four main classes

(Table 2). This step of the GIS model is an automated process, which can either be vector- or raster-based. A user-friendly software interface was developed for this stage.

Table 1. Exclusion areas buffered in the landfill GIS model. Buffer distances used in the model are allocated based on distances obtained from literature reviews. The model allows the user to enter alternative buffer distances if desired.

Exclusion areas			
1 – Non geological (antropic) factors	Buffers **(metres)**	2 – Geological and correlated factors	Buffers **(metres)**
Class A. BUILT		**Class A.** GEOMORPHOLOGICAL AND HYDROLOGICAL	
• Urban & Hi-Tech Industrial Areas: (major/minor administrative centres, areas with > 10 houses per hectare)	[400 - 6000]	• Rivers/Canals (permanent/ temporary)	[30 - 2000]
• Industrial Areas: (hazardous, manufacturing, food/agricultural)	[100 - 500]	• Floodplains	30
• Airports: (national, local, flight paths)	[10000 -13000]	• Lakes, Swamps	[300 - 1000]
• Roads: (highways, motorways, municipal, other etc.)	[30 - 600]	• Coastline	100
• Railways	[30 - 500]	• Steep Slopes (> 20°)	100
• Water Supply: (reservoirs, wells, boreholes, springs)	[300 - 1000]	**Class B.** OTHER GEOLOGICAL FACTORS	
• Military Areas	30	• Major Geological Faults: (active and potentially active, M_L >5, prone to surface rupture)	[60 - 2000]
• Public Buildings/ Infrastructures: (hospitals, schools, gas stations, treatment plants)	[30 - 100]	• Regionally important aquifers with extreme vulnerability	30
• Linear Infrastructures :(cables, pipelines, etc.)	[30 - 100]		
Class B. DESIGNATED AREAS			
• Nature Reserves: (ecological, biogenetic, etc.)	30		
• Agricultural and Game Reserves	30		
• Geological and Archaeological Reserves	30		
• Mining Areas not Suitable for Landfill	30		
• Leisure Areas: (speleological, parks, etc.)	300		

All of the criteria are labelled with numerical values for the high, moderate and low susceptibility/suitability ranges. Classes such as susceptibility to natural hazards, aquifer protection levels and land-use capability are treated as negative for landfill. Criteria within these classes are mapped according to high, moderate or low susceptibility. The geo-environmental engineering class is treated as positive for landfill. The criteria within this class are mapped according to low, moderate or high suitability.

Not all of the data sources required to carry out analyses on the residual areas may currently be available in all countries. For example, there are no flood risk maps covering Ireland or Portugal at the present time. Where there is a lack of information, expert opinion must be relied upon to map the criteria. Geo-environmental criteria, e.g. mass movements, active erosion processes, and flood prone areas were mapped using expert opinion where data were unavailable. New/improved datasets can be incorporated as and when they become available.

An extension was developed for ArcView GIS within the Interreg project that will automatically calculate the weights for each category following inputs from the user. The calculation of the weights is based on Saaty's approach, which takes into account the results of judgments made in a pair wise comparison (Saaty, 1980). Saaty's approach is used within the model as a default option. However, the model has been kept flexible to allow the user to input weights based on other methods or knowledge if preferred. Saaty's approach is considered to be one of the most reliable methods in an evaluation of alternatives in single and multi-dimensional decision making problems (Triantaphyllou, 1985).

Table 2. Classes and criteria for residual areas. The criteria are equally valid in any country.

Class	Class Description	Criteria
Class A	Susceptibility to Natural Hazards	Mass Movements; Active Erosion Processes; Volcanic Activity; Seismicity; Flood-Prone Areas;
Class B	Aquifer Protection Levels	Local Importance; Vulnerability; Recharge Areas
Class C	Land Use Capability	Agriculture & Silviculture; Ecological; Geological Resources;
Class D	Geo-Environmental Engineering	Natural Barriers; Foundation Workability; Foundation Stability Conditions; Foundation Slope Stability; Potential for Land Regeneration/Remediation Costs.

The total evaluation (*te*) of the residual areas followed the model below:

$$te = \sum_{i=1}^{cri} C_i * a_i$$

Where:

C_i : the value of criterion I
a_i : the weight for criterion i
cri : the number of criteria

The range of *te* values are divided into suitability classes using statistical methods. Different numerical values can be assigned to the criteria for successive runs of the model. A sensitivity analysis may then be carried out to evaluate if and how the outputs of each run are different. This will indicate whether the model is sufficiently stable/robust.

The Kappa statistic (κ) introduced by Cohen (1960),

$$\kappa = (\text{Map 1} - \text{Map 2}/(1 - \text{Map 2}) \qquad (2)$$

is used to quantify the degree of agreement/disagreement of the output maps (of the sensitivity analysis). An assessment of whether these differences are statistically significant, or not, follows this procedure (see Koukoulas & Blackburn, 2001). Although this process is not part of the model available to end users, it is a fundamental component of the Interreg project and tests were run to establish the robustness of the model prior to its completion.

2.2 Geotechnical evaluation

The evaluation process is concerned primarily with the geotechnical characteristics of the potential sites remaining after the screening stage(s). A detailed evaluation stage is essential to the site selection process, in order to establish the geological/hydrogeological characteristics of the natural geological materials underlying identified potential sites and will also be necessary to fulfil the requirements of an EIS. From a geological/hydrogeological standpoint, parameters determining the suitability of sites for landfill (Allen & MacCarthy, 1991) are:

- Bedrock Lithology - rock type, grainsize characteristics, texture, homogeneity, bedding characteristics, etc.
- Overburden Lithology - character, thickness and homogeneity of unconsolidated overburden.
- Hydrological Properties - of both bedrock and overburden, i.e. porosity, permeability, hydraulic conductivity, attenuation potential etc.
- Geological Structure - attitude of bedding, folding, faulting, jointing, including discontinuities on all scales.
- Hydrogeology - groundwater levels, distibution of aquifers and aquicludes, groundwater flow patterns etc.
- Surface Runoff Patterns - size and discharge of streams running through the site - controlled by the topography of the site.
- Topography - inclination of sloping sites, shelter from wind, visual impact.

This phase of the selection process will mainly involve field and laboratory investigations of the various potential sites, with particular emphasis on the following techniques :-

- Geophysical Surveys - useful in determining the characteristics and thickness of the overburden deposits.
- Hydrogeological Surveys - mainly to determine the depth to the water table and the velocity and flow regime of the groundwater
- Meteorological Programme - to determine local wind velocities and rainfall characteristics.
- Drilling Programme - required to confirm the geophysical interpretation, to obtain drill core samples for laboratory investigation, and to use for downhole geophysical measurements of porosity, permeability etc.
- Laboratory Programme - primarily to determine laboratory porosity/permeability values and to ascertain the attenuation capacities of the overburden materials.

A number of geophysical techniques are applicable to landfill site investigations. These are:

- Electrical Resistivity
    - Constant Separation Traverse (CST) - contoured resistivity map produced - displays variations in depth to bedrock.
    - Vertical Electrical Sounding (VES) - determines depth to bedrock.
- Electromagnetic methods
    - Very Low Frequency (VLF) - determines presence of fracture zones in buried bedrock.
    - VLF-R - contoured resistivity maps produced - variation in nature of overburden emphasised. Presence of shallow bedrock indicated.
- Magnetics - differentiates between rock types with significant differences in magnetic properties e.g. basalt and chalk.

Geoelectrical methods are the most useful, but are inconvenient, involving laying out of lengths of cable, which in some types of terrain may not be possible. In such circumstances, the VLF-R technique is more convenient, combining the advantages of the geoelectric methods with electromagnetic methods, which are rapid. Magnetic methods have a limited application, but are useful where different bedrock types, such as basalt and chalk, which have distinctive magnetic susceptibilities, occur (Lyle & Gibson 1994). Interpretations of overburden characteristics based on geophysical techniques need to be confirmed by drilling, as they are based on assumptions, which may not be valid in any specific case.

Hydrogeological surveys are necessary to establish the groundwater characteristics of any potential site. Parameters, which need to be ascertained, are (Dörhöfer & Siebert, 1995) :

- General groundwater flow direction
- Hydraulic gradient
- Depth to the water table
- Nature of piezometric surface (confined, unconfined)
- Presence of aquifer beneath site
- Groundwater yield
- Type of groundwater
- Vulnerability to contamination
- Permeability of the material overlying the aquifer
- Location of the site relative to the nearest receiving stream

Whilst some of the above information may be obtainable from various types of groundwater maps, it is unlikely that they will show the detail required for the evaluation of potential sites. Therefore, a thorough investigation of all known water wells and springs in the targeted areas will be essential, together with the analysis of all existing well data records. In addition it will be necessary to initiate a systematic well testing programme to determine groundwater levels, groundwater discharge patterns and particularly water quality from the earliest stages. In addition any boreholes existing in the target areas, or drilled as part of the subsequent drilling programme should be subjected to the same series of tests. Finally it may be necessary to undertake pumping tests on selected water wells to determine groundwater flow rates.

A meteorological investigation needs to be initiated early in the evaluation process, in order to obtain statistically acceptable data. This would generally involve the installation of automatic rain and wind gauges at potential sites to determine the climatic characteristics of the sites. However, prior to this, it is necessary to examine local meteorological records to determine rainfall and wind patterns. This investigation not only allows estimates to be made of the precipitation levels and wind velocities at the potential sites, it enables prediction of the recharge potential of groundwater at the sites, and the amount of rainwater which could infiltrate into the sites at any time. This can then be used to ascertain if the attenuation potential of the geological barrier is likely to be exceeded at any point. The need for shelter in the form of windbreaks either natural or artificial can also be assessed, and the types of tree species most suitable to the area surrounding the site for natural windbreaks can be evaluated, also using the overburden information obtained from drilling.

A drilling programme is the last phase of the evaluation process, which needs to be initiated, and is undertaken in order to obtain primary information on overburden characteristics, depth to bedrock and depth to the water table. However, this should only be embarked upon after all available pre-existing borehole data for the targeted areas have been collated as this will determine where drill sites are necessary. Drilling programmes within the potential sites should be constructed to confirm the bedrock and overburden geology and hydrogeological characteristics of the sites, and to determine the attenuation properties of the overburden. Also the drilling programme needs to be designed so that undisturbed drill core samples can be obtained for laboratory testing of porosity, permeability and attenuation properties. In addition, a whole series of in situ down-hole logging techniques, e.g. Single Point Resistance, Natural γ Radiation, Caliper, Fluid Temperature, Fluid Velocity and Packer and Piezometric Permeability Measurements can be employed with boreholes to give further information about subsurface units and groundwater characteristics.

A major objective of the above evaluation programme is the assessment of the earth materials underlying the potential sites as geological barriers. A whole series of tests need to be conducted on potential geological barrier materials (Dörhöfer & Siebert, 1995):

A. Field Characteristics

- Thickness of the barrier materials
- Distribution of the barrier materials
- Homogeneity of the barrier materials
- Petrography of the barrier materials
- Structure of the barrier materials

C. Attenuation Characteristics

- Hydrochemistry
- Clay mineral content
- Total porosity
- Specific surface area
- Cation exchange capacity
- Total oxygen demand
- Oxide/hydroxide content

B. Hydrogeological Characteristics

- Hydraulic conductivity (in situ)
- Hydraulic conductivity (lab)
- Effective porosity
- Hydraulic gradient
- Groundwater flow direction
- Groundwater flow velocity
- Groundwater discharge
- Depth to water table
- Groundwater potential

D. Geotechnical Characteristics

- Settlement (compressibility)
- Stability (shear strength)

Environmental impact assessments, mandatory for landfills nowadays, generally include numerous geotechnical parameters, many of which are listed above, so their inclusion within the framework of the evaluation stage obviates the need to undertake them at a later stage.

It is recommended that a computer register of the sites be developed, and databases for all geological, hydrogeological and geotechnical information collected during the course of the investigation be established. Within the register, sites should be graded on a scale of suitability, and ranked in order of preference. Deficiencies of each of the sites investigated should be clearly indicated, together with an outline of proposed compensatory mitigation strategies.

At each stage in the selection process, particularly at the outset and on completion of the screening and evaluation stages, reports should be published and distributed, and public meetings called in order to involve the public in the process. Even before initiation of the process, the public should be advised of local requirements in terms of landfills for the foreseeable future, as part of local or regional waste management plans, together with details of the criteria to be applied in the screening stage. Public participation should be encouraged, particularly with respect to the ranking and weighting of the criteria applied to residual areas. On completion of the screening stage, results should be published and further public consultation engaged in. In addition, an outline of the various components of the evaluation stage should be presented, again with the opportunity for the public to make contributions to any aspect of the evaluation process. Finally, after completion of the evaluation stage, full details of the results of the assessment of the various potential sites should be published, together with the grading in terms of suitability, and the ranking in order of preference. Public participation in the consultation process must be encouraged, and in the event of intense opposition to the preferred site, which cannot be resolved, arbitration should be sought through some statutory body

3. CONCLUSIONS

Widespread public opposition to planning applications for landfills is a recent trend manifested in a number of countries, indicating that a new approach to the selection of landfill sites must be adopted if public support for the site selection process is to be enlisted. An open and transparent multicriteria landfill site selection procedure, with public consultation and participation at all stages in the process, is essential if current public attitudes are to be reversed.

A three stage site selection procedure is proposed, consisting of computerised GIS primary and secondary screening stages, followed by a subsequent detailed evaluation stage, and integrated into regional land use planning. Natural geological barriers, particularly thick overburden sequences should be identified in the screening stages, and should be confirmed by geophysical and drilling techniques in the evaluation stage. Hydrogeological and meteorological investigations are also a necessary part of the evaluation process as are impact assessments on local communities, and the environment and ecology of the area.

Using the landfill GIS model as part of the site selection process can help to make the selection of a potential site for a landfill facility more transparent. The developed landfill GIS model fulfils the legislative and environmental obligations associated with site selection in a non-biased way, and the methodology ensures that there is a clear and scientific rationale behind the choice of a site. Including the methodology for the weighting of the criteria help to reduce the subjectivity of the exercise. The sensitivity analysis is an important step in the process as it assists in examining whether the model is sufficiently stable for operational use. The model provides a tool and a methodology for landfill site selection to local authorities, which will enable them to conduct their own GIS landfill site selection screening process.

Finally, it is stressed that the general public must be involved in the selection process from the outset, through dissemination of information, consultation and public meetings. Only then will public approval of the site selection process be gained, and the final selection be accepted.

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