Database Management and Spatial Interpolation of Geologic Boring Logs Using GIS at the Kalmar Landfill Rochester, MN.

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Abstract

Funding allocated to local government departments is often limited. As a result, data collected from required studies are extremely important and making efficient use of them even more important. Olmsted County's Solid Waste Division has chosen to develop a geologic data management system in hopes of better understanding subsurface conditions at the Kalmar Landfill. A pilot project has been initiated to organize and extrapolate data in the southern third of the landfill. This pilot project consists of two primary objectives: 1) develop a database management system for the existing and future boring logs, and 2) extrapolate the lithology data using geostatistics and interpolation methods to generate probable subsurface geologic conditions. If successful, the new tools will provide a time saving alternative to manual geologic interpolation and queries when additional data are collected. In addition, the intent is to provide a consistent naming convention for geologic descriptions, determine possible required studies that should be performed, and establish a user friendly interface for filing, retrieving, and analyzing geologic data. The initial step involved developing a database management system capable of handling existing driller's logs and additional geotechnical test results. Using this database allows for easier querying, filing, and transferring of data to modeling software. A Geographic Information System (GIS) was selected as a tool to model the subsurface, and several interpolation methods used in GIS were tested to determine an appropriate method. Results of the pilot project will lead to the development of a complete geologic database management system and enable multi-faceted evaluation of geologic conditions at the Kalmar Landfill.

Introduction

In glacial deposits, the sedimentary environment and erosional processes are often spatially heterogeneous affecting subsurface attribute interconnectedness. Knowledge of the subsurface interconnectedness is available through surface exposure mapping, point measurement (e.g., well or bore holes), and averaged hydraulic tests (pump tests) (Lall and Ali, 1996). These data types provide a nearly continuous, vertical sample of the subsurface, but are essentially only a point of the geology and aquifer in the lateral. Developing nearly continuous samples of the lateral geology or aquifer would require evenly and closely spaced point measurements. The cost and time spent implementing extensive sampling to achieve this is not often feasible for companies or government departments.

To alleviate the problem of extensive sampling, interpolation methods are often applied to expand the existing data to produce probable results. Interpolating a surface can be accomplished through several methods such as kriging, spline, triangular irregular network (TIN), and inverse distance weighted (IDW). These interpolation methods are highly dependent on the relative proximity and density of nearby sample points.

Kriging is the most computer intensive method used by Geographic Information System (GIS). It is based on the regionalized variable theory that assumes spatial variation between points is statistically homogeneous (ESRI, 1992). The variation is measured using the semi-variance, which is half of the average squared difference in a z value between sample points. (ESRI, 1992). Five different kriging methods are provided by GIS to model the semi-variance: spherical, circular, exponential, Gaussian, and linear.

Triangular irregular network (TIN) produces a series of points that are mathematically described in space with respect to their location and elevation. TIN partitions a surface into a set of contiguous, non-overlapping triangles in an attempt to satisfy the Delaunay criteria. As a result, the interpolation attempt to satisfy all sample points are connected with nearby neighbors in shortest possible manner, points are as close as possible to a node, and the triangles formation is independent of the order in which points are evaluated.

Spline enforces two conditions during interpolation: 1) The surface must pass through the data points, and 2) the surface must have minimum curvature. This method is best suited for gently varying surfaces within a short horizontal distance. Two options are available to achieve the interpolation: regularized and tension. Tension modifies the minimization criterion so first-derivative terms are incorporated into the minimization criteria (ESRI, 1992). A larger “weight” argument increases the stiffness of the interpolation to conform to existing data. In comparison, the regularized option produces a smoother surface than those created by the tension option. The regularized weighted values between 0.5 and 0 are often suitable for many interpolations, while weighted values for tension can range between 0 and 10 (ESRI, 1992).

Inverse Distance Weighted (IDW) is a local interpolation method. It assumes that each point has an influence on the interpolation; however, the influence decreases with distance. Therefore, distant points will have the least influence on an interpolation point.

General Site Information

The Kalmar Landfill is Olmsted County’s newest multi-purpose landfill located ten miles west of Rochester in Section 26, Township 107N, and Range 15W (Figure 1). Construction began in 1990 with the development of its demolition cell 1C. Following years have seen the development of additional cells for municipal solid waste and ash disposal.

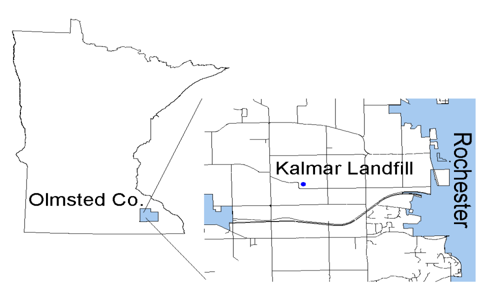


Figure 1. Site location of Kalmar Landfill.

The development of these cells has altered the topography of the site. As a result, geologic and hydrologic conditions have also been altered. Initial studies conducted by various environmental engineering consultants determined that the general subsurface geology consists of glacial till and outwash deposits.

In greater detail, the geology consists of a thin layer of topsoil in the eastern portion of the landfill and lean clay to sandy lean clay till in the western portion of the landfill (RUST, 1998). The underlying geologic layer consists of approximately 2 to 11 feet of wind-blown loess composed of silt, clay, and silty clay brown to gray in color. An upper unit of glacial till ranging from approximately 50 to 80 feet thick composed of clay and silty clay underlies the loess material with a weathered contact. Between the upper glacial till and underlying clayey till, there are discontinuous glacial outwash lenses. The southern portion of the landfill is underlain by a locally continuous sand lens. This lens is apparently absent beneath northern portions of the landfill under the ash area. Another sand lens appears separate from the upper lens in the southern portion of the landfill at a lower elevation. The lenses range from 5 to 10 feet thick and appear continuous across much of the northern portion of the landfill. It can also be identified beneath portions of the southern half.

The bedrock units underlying the landfill include the St. Peter Sandstone, Praire Du Chien, and Jordan Sandstone and are typical of southeastern Minnesota. The first bedrock layer encountered is the St. Peter Formation. Wells on the landfill do not penetrate below this formation, but based on previous geologic studies in the area the unit underlies the entire landfill. The formation consists of well-sorted white to yellow quartz sandstone.

The hydrologic setting of the landfill consists of an upper bedrock aquifer in the St. Peter formation and an underlying aquifer in the Praire Du Chien and Jordan Formation. These two aquifers appear hydraulically disconnected from the overlying water table due to the confining property of the overlying glacial till (RUST, 1998).

Since 1990, the hydrogeologic condition of the landfill has been monitored through wells drawing water from various geologic units. The entire landfill property does not have hydrologic data dating back to 1990 because monitoring wells have been installed in several phases. There are currently 17 monitoring wells, plus one production well. In addition to these wells, 11 residential wells within a mile radius are also monitored.

Groundwater records for the loess and upper glacial till units during 1997 indicated water was present at the landfill under water table conditions. The water table ranged from approximately 1158 feet above sea level in the southern portion to 1092 feet in the northern portion. Wells in the glacial outwash and lower glacial till indicated a pieziometric surface ranging from 1141 feet in the west to 1089 feet in the northeastern portion of the landfill. The overall movement of groundwater was concluded to be from the south to the northeast. Based on previous studies the outwash and lower till units appear hydraulically separate from the groundwater table due to the confining nature of the upper till unit.

In the spring of 1996 Environmental Monitoring System

(EMS) wells EMS-13 and EMS-14, were installed north of the proposed municipal solid waste cell, 2B, and unexpected ground water yield and water level results prompted further investigation. Hydraulic conductivity tests indicated these wells had some of the lowest values at the site, $3*10^{-8}$ cm/sec for EMS-14 and $2.4*10^{-17}$ cm/sec for EMS-13 (RUST, 1998). Water levels were monitored for several weeks after installation. The extremely slow recovery prompted Olmsted County to evaluate and try to correct any potential well installation problems that might have caused the discrepancy. None were found.

Eventually it was learned that the discrepancy at EMS-13 and EMS-14 was likely attributed to the unfractured nature of the till with depth. This was only determined after further evaluation of pre-existing data was difficult to compile due to the lack of a geologic data management system. As a result, an alternative method has been developed to allow quicker access to the subsurface data. This method also includes applying geostatistics and interpolation to develop a representation of the subsurface to acquire a better understanding of geometric distribution of sediment deposits.

Methods

Data Collected

Geologic information from the Kalmar Landfill was obtained from numerous boring and well logs installed during landfill construction. Contracted environmental consultants manually interpolated the geologic description from the driller's logs. These results and associated driller's log were cataloged with soil, hydraulic, and sediment analysis results into two booklets. Unfortunately, many of these results were incomplete or absent from an individual well or boring log because of the initial test requirements, funding, or log sheet format. Coping with the variation in record results was a concern in developing the database. All available information was copied into the database and when information was not found on the logs, the database field was left blank.

Additional data were obtained from the Olmsted County GIS and Survey Division. Coverages of the entire county include roads, parcels, rivers, and city limits, and were projected in Universal Transverse Mercator (UTM) in Zone 15, North American Datum 1927 (NAD27). Specific Kalmar Landfill coverages were also obtained as AutoCAD files and converted to shape files using the ArcView AutoCAD extension. Olmsted County was busy developing a conversion method during the time frame of this project. As a result, the coverages projected in Olmsted County Project Coordinate System NAD27 were not converted to NAD83 .

Data Created

The study area was designed to encompass all the wells and borings within the municipal solid waste area. An attempt was made to minimize the boundary extent beyond the outer wells or borings to less than 100 ft.

The glacial deposit on which the site resides is predominately heterogeneous. Glacial deposits from individual glacial actions can influence sediment deposition over a few miles long, a few miles wide, and orders of magnitude less in thickness. Changes in sediment deposits are predomintly in the horizontal versus the vertical, and as such, are difficult to generate as continuous surfaces. The variation in sediment deposition often includes tunnel valleys, buried outwash plains, terraces, and eskers. Interpolation between similar sediment deposits can create continuous surfaces which would eliminate the actual presence of small discontinuities as an unwanted side effect. Effectively maintaining the heterogeneity was accomplished by dividing the site into individual elevation planes at 2 foot intervals. The intent is to show changes in the well or boring description at a given elevation that will in turn influence the interpolation.

Generating the elevation plains at 2 ft intervals was accomplished using the query capability of Access97. An elevation 0.1 feet above and below the selected plain elevation would be entered to ensure the query worked correctly. Wells or borings intersected by 0.1 feet above or below an elevation plane were selected out of the database and saved to a table. Additional information about the well or borings were also placed in the output table.

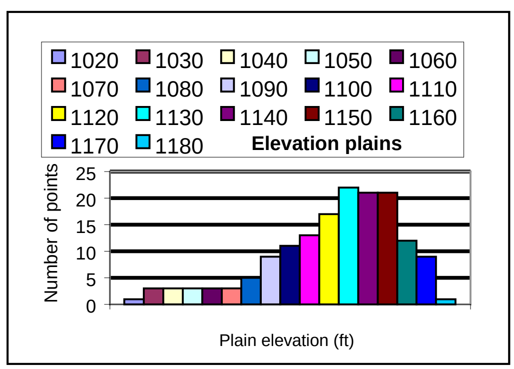
With the exception of boring B-040S, all wells and boring lithology changes were classified using the American Society for Testing and Materials Standards (ASTM) D 2487. The ASTM provides standardized methods for identifying soils/sediment based on visual examination and simple manual tests, and provides standardized terminology (RUST, 1998). The numerous classifications of sediment at Kalmar were reclassified into seven generalized categories. (Table 1).

Table 1. Reclassification of sediments

General Catogory	Code	ASTM soil/sediment Classification
Gravel	1	GM-SL
Sand	2	SM, SP-SM, SP, SC, SM-SW
Clay	3	CL, CL-ML, ClwithS
Silt	4	ML-CL, ML
Fat Clay	5	CH
Elastic Clay	6	MH
Organic	7	OL, OH, ML-OL, OL-ML

Reclassification was done using ArcInfo's capabilities to select and unselect fields in a table and calculate a new integer field if a statement is true. Once completed, interpolation on the elevation plains could begin. Elevation planes between 1180 and 1170, and 1060 and 1020 were not done in 2 ft intervals. The geometrical distribution and lack of abundant sampling points limited the interpolation process at these elevations. The abundance of points between 1170 and 1070 gradually increased and then decreased as deeper planes were constructed (Table 2).

Table 2. Abundance of well points per elevation plane in a 10 foot interval



The interpolation accuracy was performed on elevation planes containing the most distribution and abundant well samples because these planes allowed for the most complex interpolation. The default settings for the different interpolation methods were not used. Instead, a cell size of 5 feet was selected based on processing speed, file size, and geologic representation.

The spline regularized option was selected versus the tension option because it created a smoother surface that may be more representative of geologic variation in the horizontal. Interpolation with the spline method using the regularized option required alteration in the weight value to control the tautness of the curves. Values between 0.5 and 0 are often adequate (ESRI, 1992). The number of nearest points around the cell being analyzed was set to 3. It was assumed the closest wells would exert the most influence and would be more representative of the actual geology.

Interpolation using the kriging method was attempted, but semi-variogram plots were poor or the interpolation process produced illegal operations in computing. As a result, kriging was not used to interpolate. Similar poor results were achieved using IDW and as such it was not utilized as an interpolation method.

Accuracy of Analysis

The number of neighboring wells or borings affecting the interpolation was a concern because of the affect on the size and shape of the interpolated grids. Testing the affect was performed on a 10 foot interval between 1136 and 1126 feet. The individual planes contained an abundant number of wells (19 to 21) and the upper water table. A small number of wells (8 to 12) were also checked between 1100 and 1090 feet. Neighborhood samples were switched between 1 and 3 during the spline interpolation process and reclassified using the same category intervals. This was done to determine if the number of known points used to calculate a point affected the interpolation results. Other elevation planes were not checked since the majority of the planes contained sample numbers between 8 and 12.

The accuracy of the interpolation results was checked by randomly removing wells from the interpolation process. Wells were selected by reviewing a list of random numbers. If the last two digits of the number matched a well identification number, it was removed from the interpolation. The random numbers selected were 01, 08, 09, 19, 13, and 05. Since this is the identification number assigned by ArcView, the abundance of wells would determine if a well was or was not removed from the interpolation. All the selected wells could not be removed at once, so only one-fourth of the selected wells were removed at a time.

Subsurface Modeling

The combination of natural topography and altered landscape from landfill construction posed a challenge in developing a subsurface model. Well and borings were installed during different phases and, as such, represented different stages of disturbed and undisturbed topography. Subsurface material present during the well or boring installation may not be present today. To ensure some accuracy in the subsurface modeling, the original topography AutoCAD map provided by Olmsted County was compared with existing well points and clay linear elevation. The intent was to determine an elevation plane at which the subsurface had not been altered or removed. Therefore, geologic material below the determined elevation could be expected to be interpolated correctly and be representative of current conditions.

Individual planes were set to 2.5 inches in thickness. The 2.5 inches thickness was the result of the query method used in Access97 to select wells or borings intersecting the plain. The thickness was not a significant factor because geologic changes in the vertical is gradual and individual geologic log intervals all exceeded 1 foot in thickness. Furthermore, if well points were duplicated from the query, the ASTM geologic descriptions were identical.

Developing a 3-dimensional model of the study area was conducted by adding volume to the individual elevation planes. ArcView's Spatial Analyst extension calculated the area of the sediment polygon into acres and was then converted to square feet. The individual sediment polygons were then multiplied by 2 feet and expressed as a volume in meters.

Hydrologic Modeling

Geologic descriptions taken on the site provide an insight into the characteristics of the subsurface material which would otherwise be lost if examined at a lab. The moisture descriptions were evaluated to determine if they were related to ground water flow paths. The sediment description of moist or wet was reclassified into numbers with 1 equal to moist and 2 equal to wet. The same interpolation method conducted to model the subsurface was done to model areas likely to contain wet or moist sediment. The ground water table and hydraulic conductivity results were also reviewed to enhance the results

Data Discrepancies

The data for the pilot study were manually entered into the database. Particular attention was given to the data entry process to minimize the error associated with manual database entry. There are no claims the database is entirely complete in all columns, but the numeric fields used for the x, y, and z locations were entered correctly.

The study was designed to show a possible subsurface model based on the computer's interpolation. The computer results are not necessarily representative of the actual conditions. Mathematical calculations used by the computer can not interpolate a natural event in its entire detail. Therefore, results are a generalized representation of the subsurface based on the information provided.

Near the end of the project an error was discovered in the Access97 query results. The query didn't selected EMS-14, EMS-11, and EMS-3 although identical fields and columns were selected from other wells or borings. As a result these wells are not included in the study. Their absence should not dramatically effect the output of project since similar wells or borings are neighboring. To remedy the problem it is suggested that the information be re-entered and queried again.

Results and Discussion

General

A method to generate subsurface geologic conditions from well and boring logs has been pursued and illustrated. By no means is this the only available method, but to approach the heterogeneity of glacial deposits this avenue seemed appropriate. Other geologic characteristics or tests may be pursued in further studies, but particular attention should be placed on addressing depositional heterogeneity. Surfacing algorithms produce continuous surfaces and the geologic characteristics or test may not be representative of a continuous surface.

Geographic Information Systems provided numerous surfacing methods. All use different parameters to expand existing data to create surfaces. The estimated values between existing data will vary depending on the surfacing algorithm and set parameters. As such, individuals should use caution when analyzing interpolated surfaces and consider the results to be "the best fit".

Accuracy

The spline interpolation method with a weighted factor of 0.5 and sampling the three nearest neighbors produced the most appropriate interpolation of geologic sediment on a horizontal plane. Altering the neighborhood sampling for interpolation didn't significantly alter the interpolation results (Table 3). Similar results were achieved when altering the weighted factor.

Table 3. Percent of area changed from altering the number of neighbors sampled to 1.

Elev. (ft)	Percent Change for Code Sand (2)	Clay (3)	Silt (4)
1136	1	<1	3
1134	2	<1	<1
1132	11	3	13
1130	4	1	<1
1128	8	2	---
1126	8	2	---

However, spline interpolation results are strongly dependent on the number, distribution, and density of the sample points. The removal of random wells to test the accuracy of the interpolation had an impact on the results, especially when the sample point was coded differently than its neighbors. The elevation planes between 1136 and 1126 were abundant in polygons labeled clay. If the sample point was coded the same as its neighboring wells, the interpolation was not significantly affected (Tables 4 and 5). A larger percentage of change in sand and silt polygons were to some extent the result of smaller acreage, since minute changes in the size of polygon will affect the percentage of change greater than the more abundant clay polygons.

Table 4. Elevations 1136, 1128, and 1126 had code 3 removed. Elevations 1134, 1132, and 1130 had code 4 removed.

Elev.	Percent Change for Code Sand (2)	Clay (3)	Silt (4)
1136	<1	<1	<1
1134	66	7	54
1132	65	8	30
1130	7	2	28
1128	0	0	---
1126	6	4	---

Table 5. Five well points removed with varying codes

Elev.	Percent Change for Code Sand (2)	Clay (3)	Silt (4)
1136	16	11	1
1134	61	8	55
1132	18	2	26
1130	14	18	100
1128	40	10	---
1126	39	3	---

Subsurface Modeling

After reviewing the original topography and known disturbed sediment elevations caused by landfill development, the highest undisturbed sediment elevation plane was concluded to be at 1136 feet. The only known disturbed zones below this elevation were found in cells 1B and 2B, where a clay liner was installed. The majority of the material affected by the linear insulation was classified as clay.

The addition of height to the interpolated sediment polygons provided information on sediment volume. The best volume estimates were recorded in the first 20 feet of the study because the volume estimates were directly affected by the density, distribution, and abundance of sample points. Here, the number of sample points ranged from 13 to 20. The estimates at deeper depths gradually decrease in accuracy resulting from a reduction in the number of sample points. But, at the same time, these were the best results using the existing data. As such, the paper will focus on the results from the first ten feet.

The majority of sediment underlying the study area between 1136 and 1126 feet was classified as clay (Figure 2). The clay (code 3) distribution between individual elevation planes was successfully interpolated because of its abundant sample points. Other coded values 1 (gravel), 2 (sand), 4 (silt), and 7 (Organics) were not well represented in the interpolation process. Difficulties in representing these codes were partially the result of fewer sample points and the longer distance between similar neighbors. However, based on the existing data, 99,076 cubic meters of silt material is present between 1136 and 1130 feet, 569,599 cubic meters of clay, and 143,677 cubic meters of sand (Table 6).

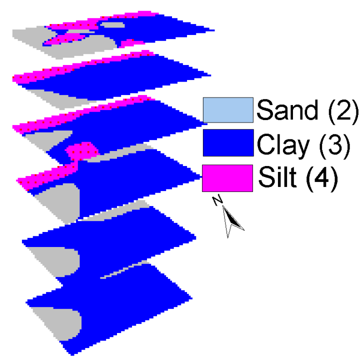


Figure 2. Interpolated layers from 1136 to 1126 feet.

Table 6. Volume results expressed in cubic meters

Elev (ft)	Code Sand (2)	Clay (3)	Silt (4)
1136	42,111	58,398	29,337
1134	1,0048	97,349	25,287
1132	9,967	94,944	31,222
1130	28,491	95,975	13,230
1128	26,530	111,465	-------
1126	26,530	111,465	-------
Total	143677	569596	99076

The clay material comprises 70.1 % of the sediment, sand 17.9 %, and silt 12.2 Understanding the abundance and distribution of these sediments is important when determining well or boring placement. The planner will have a better understanding of the thickness and area in which a particular sediment type may likely be found.

Hydrologic modeling

Preferred ground water flow paths and the presence of the water table could not be inferred by the interpolation of moist and wet sediment characteristics. Based on the interpolation, wet sediment may be found in an elongated oval area extending under the clay liner of cells 1A and 2A. A similar pattern may be seen at 1132 feet, but below 1130 feet sediments under cells 1A and cell 2A were described as moist or wet (Figure 3).

The presence of water was not limited to a specific sediment type. Sand, clay, and silt were each described as wet or moist. Clay sediment was not described as wet more than moist, but the silt was primarily considered wet. If this is the case, a specific sediment type can not be considered as an avenue of preferential ground water movement.

A better measure of preferred flow path is to examine hydraulic conductivity or permeability. Cross-referencing the limited hydrologic conductivity test data with the interpolated wet and moist zones produced similar results except in the vicinity of EMS-13 and EMS-14. Here the interpolation process produced an area of sediment described as being wet in a localized area of low conductivity.

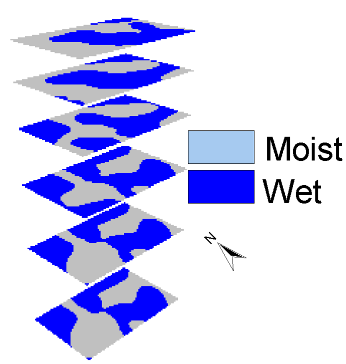


Figure 3. Interpolated potential ground water flow.

Potential for Use

The GIS was effective in presenting the subsurface geology. The ease and fast interpolation process provided by GIS is far superior to the tedious manual interpolation method. One long-term benefit of having the model in place is the potential for an easy transition into modeling contaminant plume dispersal. Additional benefits will be derived at least benefit from the database management system. Prior to the development of the Access97 geologic database, an individual requiring information about a well or wells needed to review files and books to assemble data. Now, the individual may query the database for the required information and print the results. The long-term affects of the database will be seen in eliminating duplicated tests, finding data gaps, faster reports, improved report graphics, and better time management.

Hopefully the work presented here will improve the understanding of the interconnectedness of the Kalmar Landfill glacial deposit and encourage further development of simple methods and tools. As additional wells and borings are added to the database, a more accurate representation of the actual subsurface can be generated. Until then, interpolation is the best method to visualize the subsurface.

Acknowledgements

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