FIELDS Statistical Evaluation Report: South Minneapolis Soil Contamination Superfund Site

Minneapolis, Minnesota

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Introduction

The South Minneapolis Soil Contamination Superfund Site, located in Minneapolis, Minnesota, contains elevated concentrations of Arsenic in the surface soils. From the 1930s through the 1960s, the CMC Heartland Light Yard facility (CMC) produced Arsenic-containing pesticides at a site in South Minneapolis. At this site Arsenic was transported via railcars, conveyor belts, and vehicular traffic. It is also believed that, during site activity, Arsenic may have been stored outdoors in large piles (Geomega, 2004). Collectively, these activities may have resulted in air dispersion of Arsenic into the neighboring residential and commercial properties. In the 1990s, Arsenic was detected in soil at the CMC site at concentrations up to 3,000 times greater than background levels. The state of Minnesota recognized the impacts that the elevated Arsenic concentrations posed to human health and the environment and began sampling surface soils at nearby residential properties for Arsenic concentrations. The CMC site was remediated from October 2004 through July 2005 by CMC Heartland Partners and U.S. Borax, as required by the Minnesota Department of Agriculture (MDA). Following the remediation of the CMC property, state and federal (U.S. EPA) agencies continued sampling for Arsenic concentrations in the residential surface soils surrounding the CMC site in order to identify the source and extent of Arsenic contamination.

Surface soil samples discussed in this report were collected between 2001 and 2006 by the State of Minnesota and the U.S. EPA. During this time, a total of 8,076 samples were analyzed from 3,575 properties within a 1 mile radius of the CMC site (Figure 1). Samples were analyzed using EPA method SW-846-6020 for Arsenic concentrations. As of December 2006, a total of 196 properties were identified that contained Arsenic concentrations greater than 95 ppm in surface soils. Removal actions at these properties commenced in October 2004 and were continuing at the time of this report.

Between August 2005 and December 2006, the U.S. EPA FIELDS Group assisted in determining if elevated residential Arsenic soil concentrations were attributable to the CMC site. In conjunction with previously reported statistical evaluations of the South Minneapolis Soil Contamination Superfund Site (CH2MHill, 2006), the FIELDS Group presents results of statistical evaluations of the residential soil samples surrounding the CMC site. These evaluations include the application of an air dispersion model, geostatistical analyses in the forms of semivariogram analyses and kriging, spatial cluster analyses and measures of localized variability, and correlations between residential Arsenic concentrations and property age. All analyses were performed at one of two spatial scales: either at a small scale using total observed soil sample analytical results (N = 8,076; Figure 1) or at the yard-scale using the maximum Arsenic concentration within each residential property (N = 3,313; Figure 2). Unless otherwise noted, all concentrations are in mg/kg (ppm).

Methods

Air Dispersion Modeling

The objective of the air dispersion model was to determine the primary directions in which air-dispersed Arsenic may have been transported from the CMC site to the surrounding residential properties. To model the dispersion of Arsenic from the CMC site, the FIELDS Group used the EPA Industrial Source Complex Model (ISC3). ISC3 is a Gaussian plume steady-state model, capable of estimating close-distance impacts from industrial sources (US EPA, 1995). This model can accommodate simple point source emission rates from stacks, as well as emission rates from piles, vents, and conveyor belts. Input parameters include meteorological data (wind speed, direction, etc.) as well as source and contaminant input parameters. ISC3 can predict period average concentrations as a function of distance from the source.

Following EPA recommendations, the meteorological data used in the modeling process were gathered over a 7-year period (1984 – 1990) for the Minneapolis/St. Paul International Airport (US EPA, 1995). The meteorological data were configured for direct input into ISC3 using the meteorological preprocessing application PCRAMMET (US EPA, 1999). A run-stream input file was created to be imported into ISC3, which specifies model control options, describes the source parameters, specifies the number of receptors and their locations, and identifies the meteorological data used. A receptor grid of 180 radial samples was determined at a 10-degree flow vector around the CMC site at 100 m, 250 m, 500 m, 1000 m, and 1600 m radial distances. Source inputs for the model included the estimated emission rate and the size (area) of the source. During the time of site activity, previous reports have estimated Arsenic emissions from the CMC site at a rate of 1.91×10^{-4} g/sec/m^2 within a 17 x 150 m area where railcar switching and handling occurred (Geomega, 2004). The source and meteorological data were used as input to the ISC3 model. The ISC3 model was programmed to calculate a single period average for Arsenic dispersion. A geographic information system (GIS) was then used to display the predicted Arsenic dispersion along the receptor grid network. At each radial distance, the model output was rank-transformed and a natural neighbor interpolation was performed on the ranks to visualize predominant dispersion patterns. The interpolation was performed using the FIELDS Tools for ArcView 3.x (FIELDS, 2007).

Geostatistical Analyses

The objectives of the geostatistical methods included: 1) To determine if spatial relationships existed among the soil sample results, 2) To determine if directionality (anisotropy) existed within the soil sample results and if directionality was consistent with the predicted dispersion directions from the air-dispersion model, and 3) To estimate the amount of uncertainty at different locations by investigating ordinary kriging errors. The semivariogram is a geostatistical method to determine the spatial autocorrelation among data (EPA, 2004). As a preliminary step in the kriging process, one useful tool in conducting semivariogram analysis is to determine if anisotropy, or directionality, exists in the dataset. Anisotropy exists if spatial relationships differ in varying directions. Anisotropy in soil contamination can be caused by underlying physical processes that operate differently in space, such as prevailing winds, resulting in differential spatial relationships among data points at different directions (Goovaerts, 1997; Myers, 1997). Therefore, the FIELDS Group investigated the anisotropic effects on the semivariogram and compared these results to the output of the air dispersion model.

Another geostatistical method, ordinary kriging, was employed to estimate the amount of variability in sample results at different locations. Kriging is a stochastic modeling procedure, advantageous over other contemporary deterministic procedures because kriging not only models the sample predictions, but also allows the user to model the error variances for the predictions (i.e., kriging errors; Goovaerts, 1997; Myers, 1997). As such, kriging is often recommended by the U.S. EPA to characterize contaminated soils (US EPA, 1992, 2004). The FIELDS Group used ordinary kriging to calculate and display the kriged errors (prediction error) for each location analyzed around the CMC site. This procedure was used to illustrate areas of greatest uncertainty in predicted surface soil Arsenic concentrations surrounding the CMC site. For these geostatistical analyses, soil sample analytical results were $\log_{10}$-transformed and a spherical model was selected in each semivariogram. An isotropic model (no directionality) was used for the ordinary kriging procedure. These geostatistical models were created using the Geostatistical Analyst extension for ArcGIS 9.1 (ESRI, 2005a).

Cluster Analyses and Variability Measures

A geographic information system (GIS) was used to apply spatial cluster analyses and determine measures of local variability for the soil sample analytical Arsenic concentrations. Specifically, three metrics were calculated and displayed: the Moran's I statistic, the Gettis-Ord General G statistic ("Hot Spot Analysis"), and the Anselin Local Moran's I statistic. The Moran's I statistic is a standardized measure of the global spatial autotcorrelation between neighboring features and indicates whether a feature is clustered, dispersed, or random. Negative values indicate a negative spatial autocorrelation, values near zero indicate no spatial relationship, and positive values indicate positive spatial autocorrelation. The Hot Spot Analysis shows areas where higher (or lower) than average values tend to be found near each other. The Anselin Local Moran's I statistic is a cluster analysis showing the small-scale (local) variability in the features. Using this statistic, negative values indicate that the feature is dissimilar to its neighbors, positive values indicate that the feature is similar to its neighbors, and values near zero indicates no similarity / dissimilarity between that feature and its neighbors (ESRI, 2005b). Each metric was calculated at the yard-scale using the maximum Arsenic concentration (N = 3,313). These metrics were calculated using the Spatial Analyst tools for ArcGIS 9.1 (ESRI, 2005a). All analyses were calculated within a 100 m distance band.

Correlations with Housing Age

Because pesticide formulation activities ceased at the CMC site in the 1960's, the creation of homes since that time may have affected the Arsenic concentrations in the surface soils on those constructed properties. Therefore, residential property age may be an indication of surface soil Arsenic concentrations, where older residential properties that existed during the time of site activity may have greater surface soil Arsenic concentrations than residential properties that have been constructed in the last 40 years.

Property age and spatial data were obtained from a Hennepin County parcel map, current through August 2005. For the purposes of this report, residential properties were considered as all apartments, condominiums, duplexes, townhouses, and single family residences. The age of sampled residential properties was analyzed aspatially and spatially. Aspatial analyses included correlations between Arsenic concentrations and property age and graphical evaluations of the relationship between Arsenic concentrations and house age. The maximum Arsenic concentration per residential property was used (N = 3,313). Statistical correlations (Pearson and Spearman) were calculated to determine the relationship between Arsenic concentrations and house age. Binary logistic regression was then used to determine if the probability of Arsenic concentrations exceeding 95 ppm was independent of house age. In the logistic regression procedure, house age was categorized into two predictor variables: older homes existing during site activity (> 42 yr. old) and homes created after site activity ($\leq$ 42 yr. old). The dependent variable for this analysis was the binary Arsenic concentration (i.e., < 95 ppm or $\geq$ 95 ppm).

Spatial analyses for the age of sampled residential properties included the calculation of the global Moran's I statistic to determine the spatial autocorrelation among homes. Graphical representations were also used to evaluate the spatial relationships in housing age.

Results

Air Dispersion Modeling

Results of the ISC model were rank-transformed at each radial distance from the CMC facility to visualize predominant dispersion patterns (Figure 3A). The natural neighbor interpolation of the rank-transformed data indicates a clear dispersion pattern, with predominant northwest-southeast directionality (Figure 3B). This dispersion pattern supports the results of Geomega (2004), which presented windrose plots to illustrate that the predominant dispersion direction was to the northwest of the CMC site. Therefore, if the primary mechanism for Arsenic transport from the CMC site were air-dispersion, then greater soil Arsenic concentrations are expected to occur in the properties to the northwest and southeast of the site.

Geostatistical Analyses

Semivariograms of the soil sample analytical results are shown in Figure 4. Anisotropy was evaluated in the semivariogram for 4 directions: northeast (45-degrees), southeast (135degrees), southwest (225-degrees), and northwest (315-degrees), where 0-degrees corresponds to true north. In each semivariogram, the nugget is greater than 50% of the sill and the range is very small (Figure 4). The nugget, equivalent to the Y-intercept in the semivariogram, represents unexplained variability in the model. Therefore, a greater nugget increases the error in model predictions (Goovaerts, 1997; Myers, 1997). The range, evident by the asymptote in the semivariogram, indicates the distance at which samples are correlated. A short range in each semivariogram indicates that the soil samples are correlated at only small distances.

In the isotropic semivariogram, the sample results exhibit a small degree of spatial correlation, with a nugget approaching 60% of the sill (Figure 4A). A similar correlation structure is observed in the 135-degree (southeast) and 315-degree (northwest) anisotropic semivariograms (Figure 4C, E). In these semivariograms, nearly 40% of the variability in Arsenic concentrations can be explained by the spatial arrangement of the samples. However, the 45-degree (northeast) and 225-degree (southwest) anisotropic semivariograms contain greater unexplained variability, as the nuggets in these models approach 80% (Figure 4B, D). In these semivariograms, only 20% of the variability in Arsenic concentrations can be explained by the spatial arrangement of the samples. While the samples are only correlated at small scales, the strongest anisotropic effects appear to occur in the 135-degree (southeast) and 315-degree (northwest) directions.

Standard errors of the kriged estimated Arsenic concentrations are shown in Figure 5. Areas with greater amounts of error are usually large unsampled areas or indicate areas of higher local variability (Goovaerts, 1997; Myers, 1997). A few noticeable large areas have high standard errors that are likely the result of sample paucity. These areas include the large area immediately to the east and southeast of the CMC site, the large area at the southwestern-most extent of the map, and two moderately size areas at the eastern-most extent of the map (Figure 5). Closer examination of the sample distribution reveals that very few samples were collected from these locations (Figure 1). Other noticeable areas of high standard errors occur in isolated islands or clusters where errors are great at very short distances. This phenomenon is often termed the "Swiss-Cheese Effect", and represents areas with greater local variability (Myers, 1997). Most obviously, this pattern is located near the southern extent of the map, with less noticeable areas located to the west and northwest of the CMC facility (Figure 5).

Cluster Analyses and Variability Measures

The Moran's I analysis, which determined the pattern of the Arsenic concentrations at the yard-scale (N = 3,313), resulted in a positive index value of I = 0.04. Although this value is close to zero, this result is statistically significant (Z = 12.6; $P < 0.01$), suggesting a clustered distribution of surface soil Arsenic concentrations. However, the low index value (I = 0.04) indicates that this spatial relationship is weak. Small-scale variability in Arsenic concentrations is the most likely cause of the low index value.

The Hot Spot Analysis, which determined where higher (or lower) than average Arsenic concentrations tended to be located together, resulted in a positive value of G = 0.02. Although this value is close to zero, the observation is statistically significant (Z = 6.1; P < 0.01), suggesting that higher-than-average Arsenic concentrations are found closer together. The spatial distribution of the G-value indicates that higher Arsenic concentrations tended to be clustered south of the CMC site (Figure 6). Due to the low statistic (G = 0.02), however, this is a weak spatial pattern and the spatial distribution of the G-value (Figure 6) should not be interpreted without considering the small-scale variability located throughout the map.

The Anselin Local Moran's I analysis, which identifies areas of local variability, revealed the strongest areas of similarity and dissimilarity in Arsenic concentrations among residential properties. Overall, Arsenic concentrations were neither similar nor dissimilar to neighboring properties (Figure 7). Properties with Arsenic concentrations most similar to neighboring properties occurred more frequently to the south of the CMC site, interspersed by constant and dissimilar properties (Figure 7). It is in this area – south of the CMC site – where the greatest local variability occurs.

Correlations with Housing Age

A scatter-plot of maximum Arsenic concentration versus home age indicates a gradual increase in Arsenic concentrations with an increase in the age of the property (Figure 8). Furthermore, there is a weak, yet significant, positive correlation between concentrations and housing age (Pearson Correlation, r = 0.05, $P = 0.004$; Spearman Correlation, r = 0.06, $P = 0.0002$). Further investigation of this relationship indicated that proportionally more older homes (> 42 yr. old) contain Arsenic concentrations above 95 ppm than newly created homes (< 42 yr. old) (Figure 8). A binary logistic regression was performed to determine if the probability of Arsenic concentrations exceeding 95 ppm was equal between older and newer homes. The results of this analysis indicated that older homes had a higher probability of containing surface soil Arsenic concentrations exceeding 95 ppm than newer homes ($X^2 = 15.07$; $P < 0.001$). Furthermore, an odds ratio estimate of 15.9 indicated that older homes were nearly 16-times more likely than newer homes to contain surface soil Arsenic concentrations above 95 ppm (Figure 9).

The distribution of house ages among residential properties sampled is shown in Figure 10. Of the 3,313 residential properties sampled, fewer than 20% of the homes are less than 50 years old, whereas nearly 60% of the homes are greater than 100 years old. This distribution shows that most of the house construction in the neighborhoods surrounding the CMC site occurred during a 30-yr period between 110 and 80 years ago (Figure 10). The Moran's Index, calculated to determine if the age of houses were spatially autocorrelated, revealed that house ages were clustered ($I = 0.05$; $Z = 39.1$; $P < 0.01$). Due to the low index value, however, this relationship is rendered a weak pattern. Inspection of the spatial distribution of house ages among residential properties sampled reveals that, for the most part, the ages of homes are randomly distributed throughout the study area (Figure 11). There appears to be slight clustering of older homes (> 100 yr) in the residential properties northwest of the CMC site, while homes of intermediate age (43 – 99 yr) appear to be aggregated south of the CMC site. Newer homes (< 43 yr) appear to be randomly distributed throughout the study area (Figure 11).

Conclusion

Results of the air-dispersion model indicate that wind directions were oriented towards the northwest-southeast within the study area surrounding the CMC site (Figure 3). Therefore, if wind dispersion were a primary transport mechanism for releasing Arsenic into to surface soils surrounding the CMC facility then it is likely that anisotropy, or directionality, would be present within the residential soil samples collected for Arsenic concentrations. Results of the semivariogram analyses indicate that the spatial correlation of Arsenic samples is stronger in the southeast (135-degrees) and northwest (315-degrees) semivariogram models than in the northeast (45-degrees) and southwest (225-degrees) models (Figure 4 B-E). However, all inspected semivariogram models showed very weak spatial correlations, as less than 50% of all variability in Arsenic concentrations was explained by the spatial relationships of the samples. Furthermore, the isotropic (non-directional) semivariogram appeared to show the greatest spatial correlation among the soil sample data (Figure 4 A). Therefore, although there is weak directionality among the soil samples, this pattern does not best explain the variability in Arsenic concentrations.

To quantify small-scale spatial variability in Arsenic concentrations, the FIELDS Group 1) investigated the standard errors of kriged Arsenic concentrations, and 2) calculated the Anselin Local Moran's I value for each residential property sampled. Areas greatly impacted with Arsenic concentrations may contain more variable concentrations than areas with background concentrations. Therefore, variability measures may provide a means to distinguish between impacted and non-impacted locations. The standard errors of the kriged Arsenic concentrations reveal that the greatest variability in Arsenic concentrations occurs in large unsampled areas near the CMC site and near the extents of the study area (Figure 5). The other noticeable areas of high standard errors are isolated islands of high variability within very short distances, located south and northwest of the CMC site (Figure 5). This pattern is consistent with small-scale sample variability. Another measure of small-scale variability, the Anselin Local Moran's I, assigned an index value to each residential property sampled. Properties with Arsenic concentrations that are similar to the concentrations at neighboring properties receive a positive index value, whereas negative index values indicate that Arsenic concentrations at one property are more dissimilar than concentrations as neighboring properties. According to this metric, the area with the greatest local variability was south of the CMC site, where frequent similar Arsenic concentrations were interspersed with constant and dissimilar Arsenic concentrations (Figure 7). Collectively, these results indicate that small-scale variability in Arsenic concentrations is prevalent in the areas south and northwest of the CMC site. These areas could be considered impacted from anthropogenic Arsenic sources, including the CMC site. However, this small-scale variability is not negatively related to distance from the CMC site (Figure 7), as would be expected if air-dispersion were a primary transport mechanism. Therefore, these areas of small-scale variability may be indicators of alternate anthropogenic sources of Arsenic (e.g., pesticide application).

Spatial cluster analyses were conducted to determine if spatial patterning of the Arsenic concentrations exists. The Moran's index and the Getis-Ord General G statistic ("Hot Spot Analysis") were both statistically significant for residential properties sampled. The Moran's index indicated that Arsenic concentrations were weakly clustered together, as evident by a slightly positive index value ($I = 0.04$). The Hot Spot Analysis further indicated that higher Arsenic concentrations south of the CMC site tended to be clustered together, although this relationship is very weak ($G = 0.02$; Figure 6). Furthermore, the higher Arsenic concentrations tend to be clustered at the southern-most extent of the study area – rather than in closer proximity to the CMC site – which would be expected assuming air-dispersion as the primary transport mechanism.

To investigate whether human land-use practices may have influenced the soil chemistry, and resulting surface soil Arsenic concentrations, the FIELDS Group correlated Arsenic concentrations with housing age at residential properties sampled and attempted to illustrate any spatial patterns in house age. Nearly 60% of all homes were greater than 100 years old and less than 20% of all homes were under 50 years old (Figure 10). Overall, there were very weak positive correlations between surface soil Arsenic concentrations and housing age (Figure 8). Furthermore, logistic regression analysis indicated that older homes that existed during site activity had a greater probability than newer homes of containing high Arsenic concentrations (Figure 9). Despite this relationship between Arsenic concentration and housing age, there appears to be little spatial clustering of homes throughout the study area (Figure 11), which confounds attempts to attribute Arsenic-house age relationships to the CMC site.

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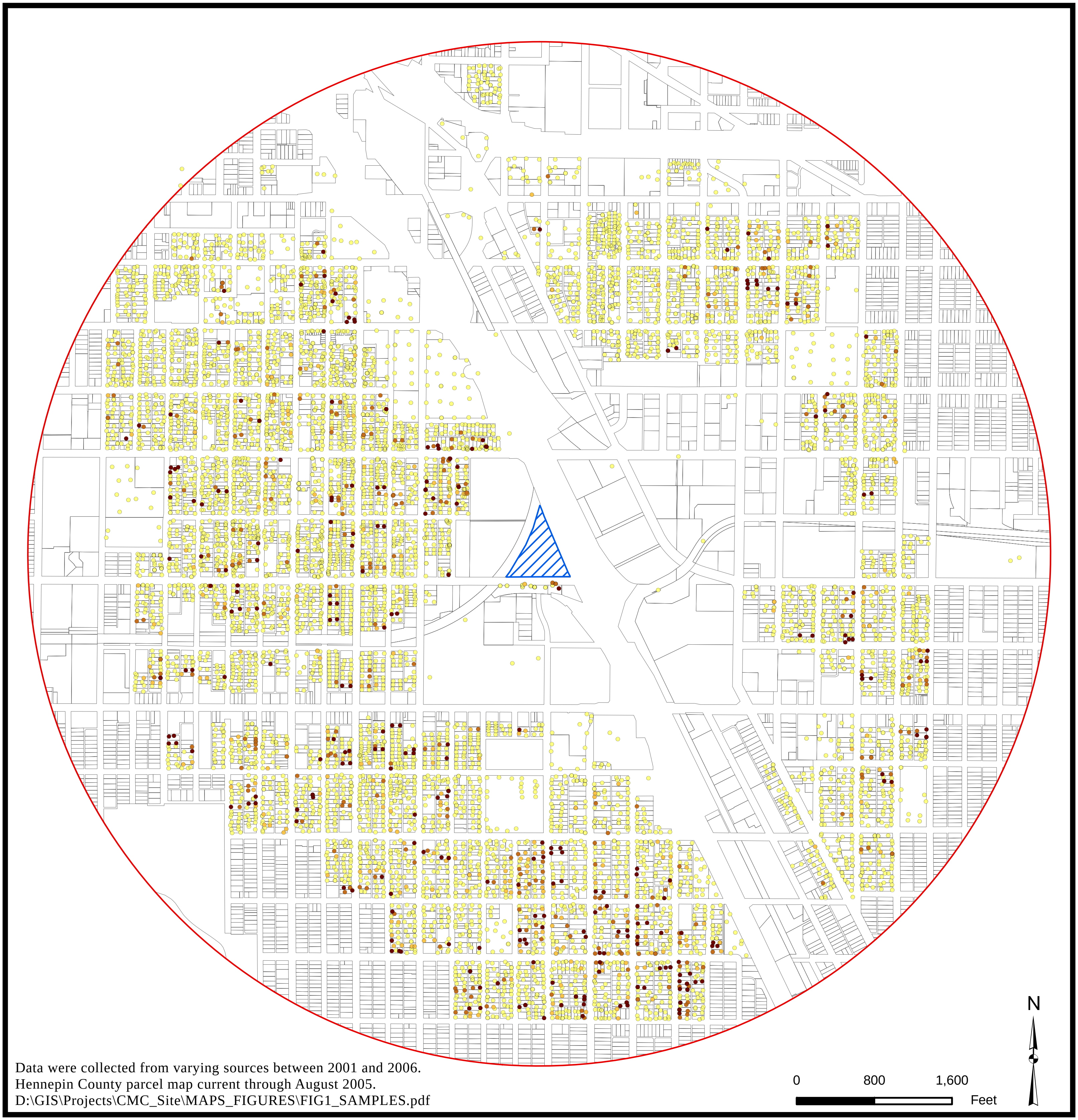
FIGURES



SOUTH MINNEAPOLIS SOIL CONTAMINATION SITE

Minneapolis, Minnesota

Spatial distribution of surface soil samples in properties within 1 mile of the CMC site.

Surface Soil Samples

Arsenic Concentration (ppm)

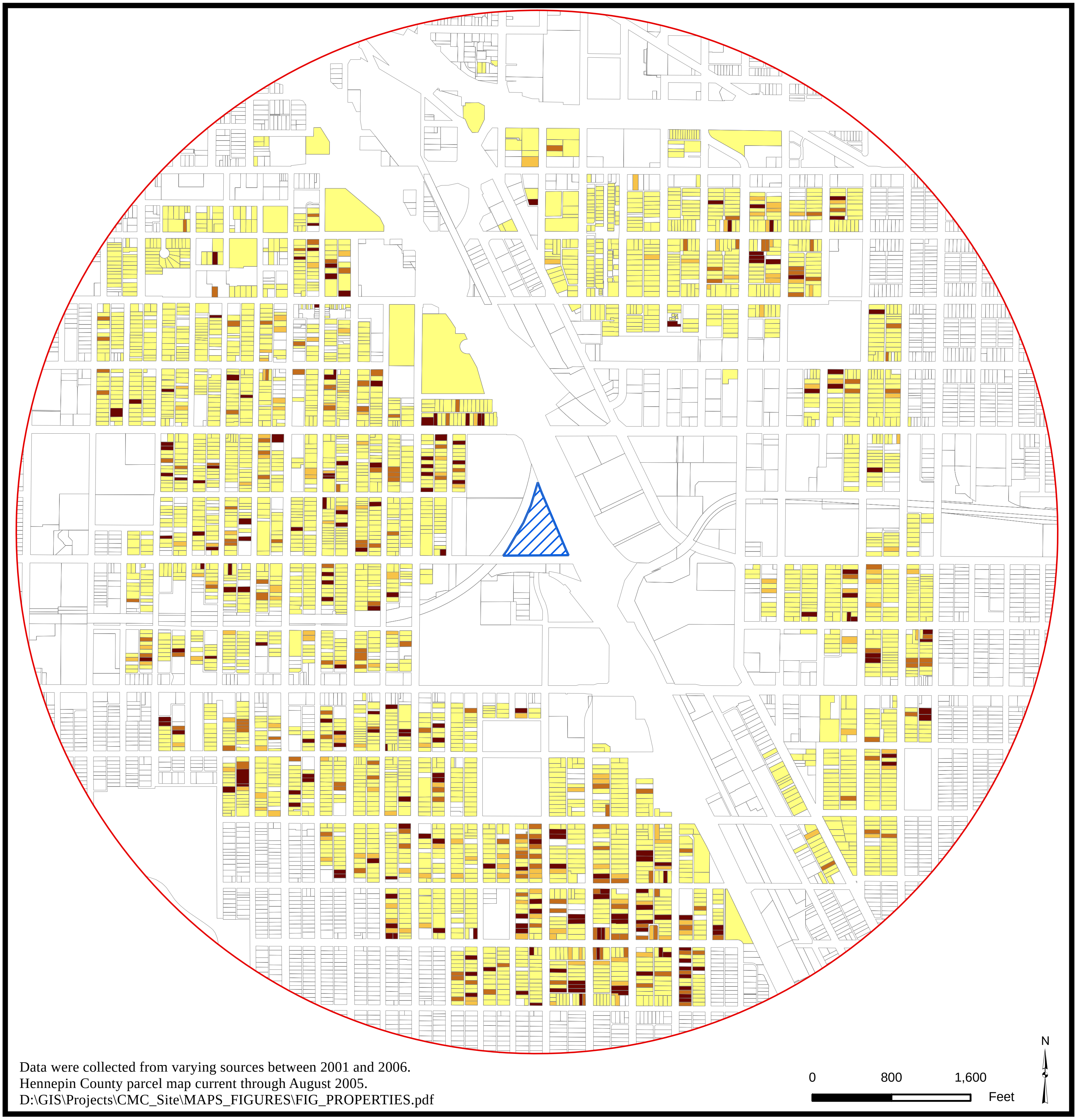
- 0 - 29.9
- 30 - 49.9
- 50 - 94.9
- > 94.9

1 Mile Radius

CMC Site

Hennepin County Properties

Figure Number: 1



SOUTH MINNEAPOLIS SOIL CONTAMINATION SITE

Minneapolis, Minnesota
Sampled Residential Properties (N = 3,313).

MAXIMUM ARSENIC
CONCENTRATION (PPM)

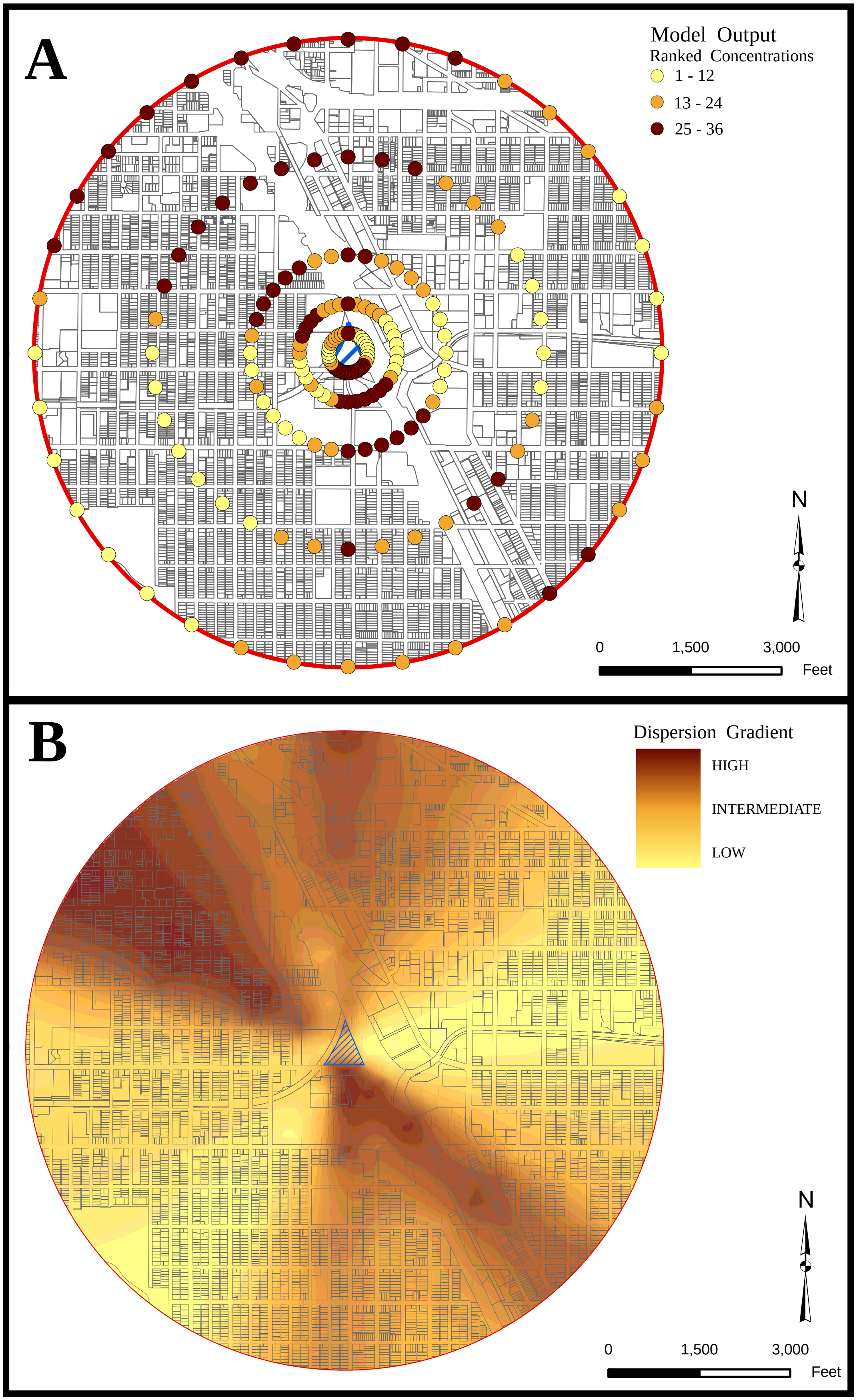
- 0 - 29.9 PPM
- 30 - 49.9 PPM
- 50 - 94.9 PPM
- > 95 PPM

1 Mile Radius

CMC Site

Hennepin County Properties

Figure Number: 2



Model: EPA Industrial Source Complex.
Input parameters collected from various sources.
Hennepin County parcel map current through August 2005.
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SOUTH MINNEAPOLIS SOIL CONTAMINATION SITE

Minneapolis, Minnesota

A) Rank-transformed model output concentrations at each radial distance.
B) Natural neighbor interpolation of rank-transformed arsenic concentrations.

1 Mile Radius
CMC Site
Hennepin County Properties

Figure Number: 3

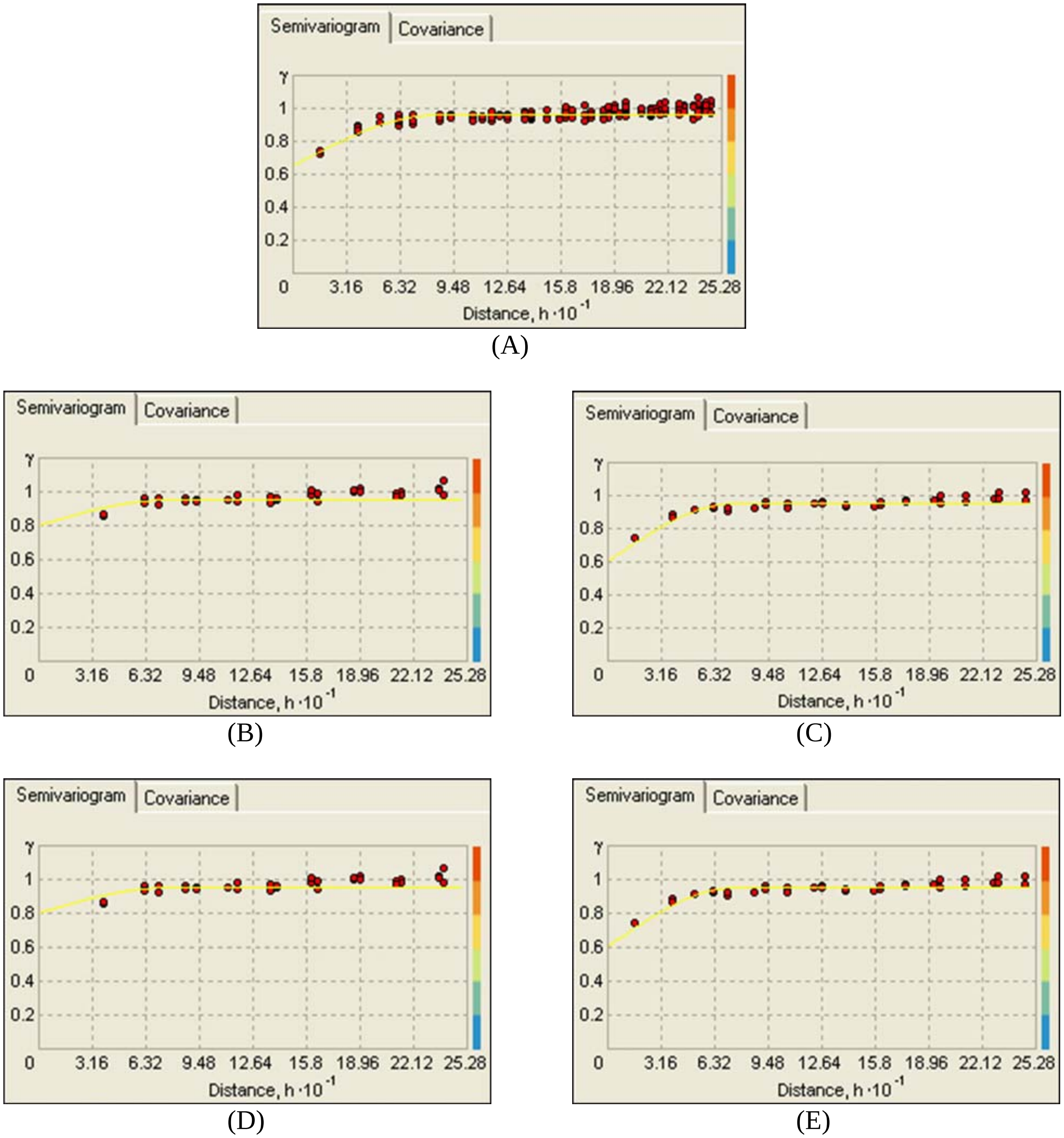
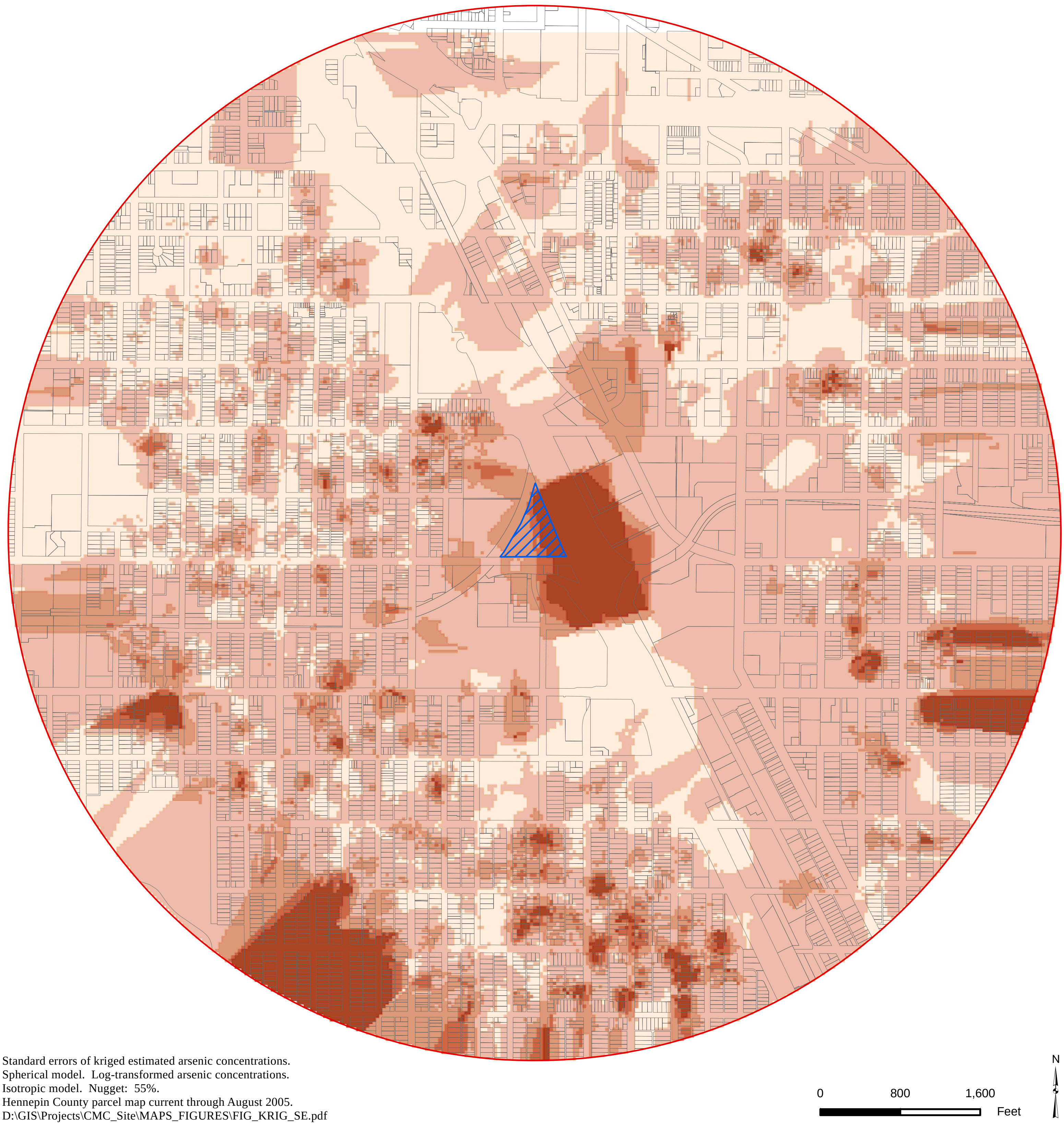


Figure 4. Semivariograms for the soil sample analytical results. A) Isotropic model. B) Northeast (45-degree) anisotropy. C) Southeast (135-degree) anisotropy. D) Southwest (225-degree) anisotropy. E) Northwest (315-degree) anisotropy. In all models, 0-degrees corresponds to true north.



Standard errors of kriged estimated arsenic concentrations.
Spherical model. Log-transformed arsenic concentrations.
Isotropic model. Nugget: 55%.
Hennepin County parcel map current through August 2005.
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SOUTH MINNEAPOLIS SOIL CONTAMINATION SITE

Minneapolis, Minnesota

Standard errors of kriged arsenic concentrations in residential surface soil samples.

Ordinary Kriging

Standard Error (SE)

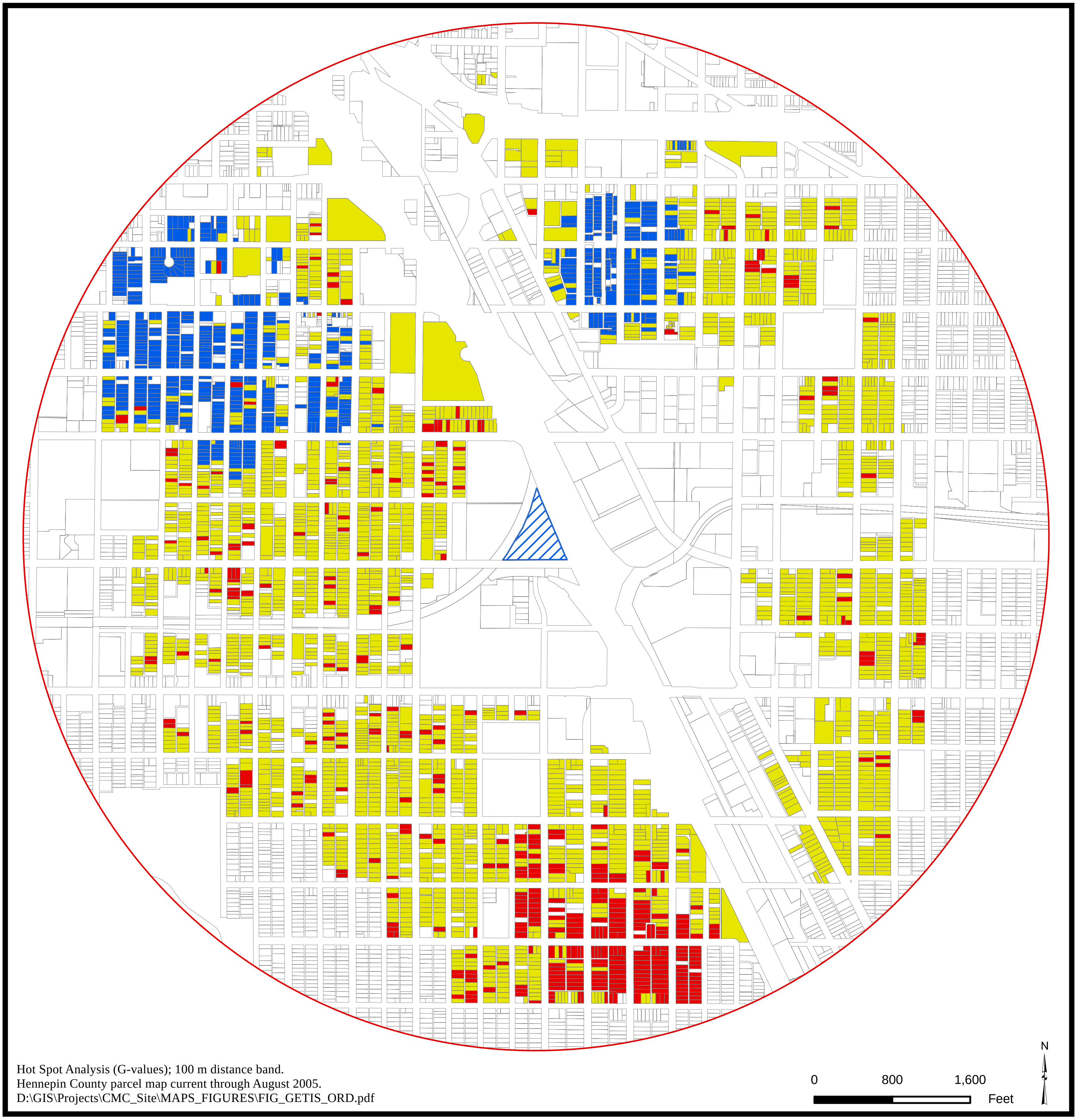
- 0 - 9.9
- 10 - 24.9
- 25 - 49.9
- 50 - 74.9
- > 75

CMC Block Grid

CMC Site

Hennepin County Properties

Figure Number: 5



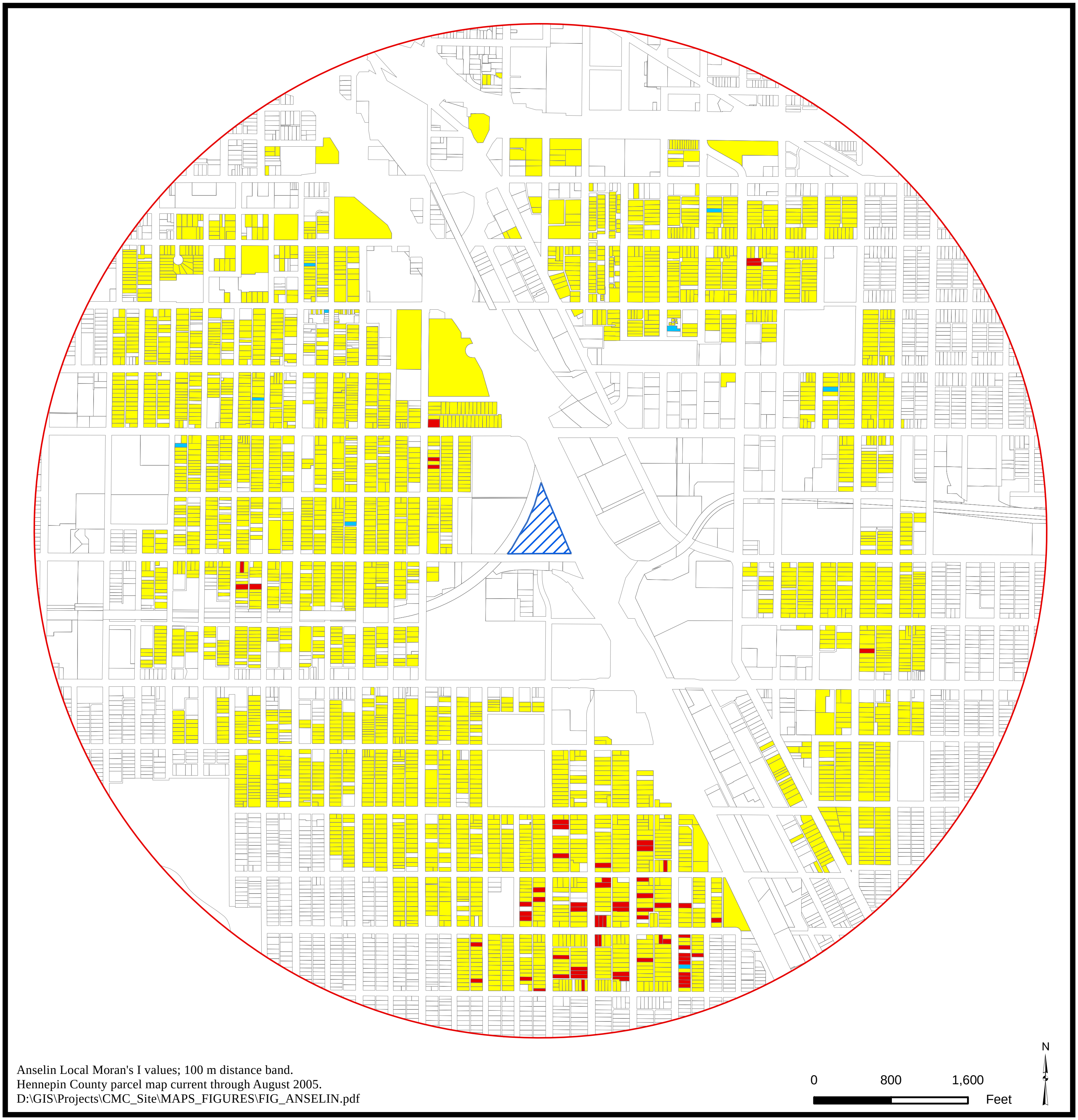
SOUTH MINNEAPOLIS SOIL CONTAMINATION SITE

Minneapolis, Minnesota
Getis-Ord G-Values for residential properties sampled (N = 3,313).

Residential Properties Sampled
Getis-Ord General G-Values
- < -2.5 (Low value clustering)
- -1.0 - 1.0 (No clustering)
- > 2.5 (High value clustering)

- 1 Mile Radius
- CMC Site
- Hennepin County Properties

Figure Number: 6



SOUTH MINNEAPOLIS SOIL CONTAMINATION SITE

Minneapolis, Minnesota

Anselin Local Moran's Index values for residential properties sampled (N = 3,313).

Residential Properties Sampled

Anselin Local Moran's Index Value

< -0.5 (Dissimilar)

-0.5 - 0.5 (Neither Similar nor Dissimilar)

> 0.5 (Similar)

1 Mile Radius

CMC Site

Hennepin County Properties

Figure Number: 7

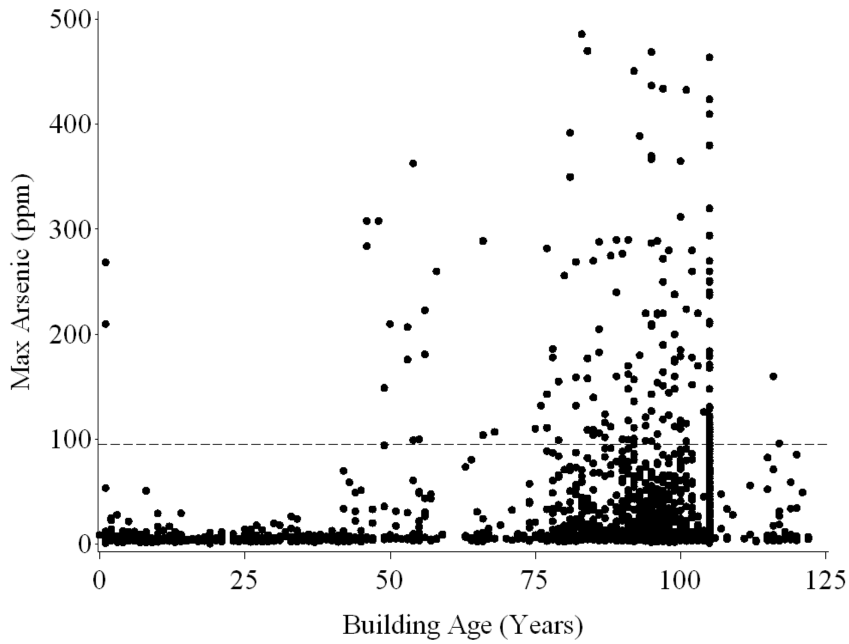


Figure 8. Scatter-plot of Arsenic concentrations versus housing age at residential properties sampled (N=3,313). Only the maximum Arsenic concentration was used. The dashed reference line indicates the 95 ppm residential action level.

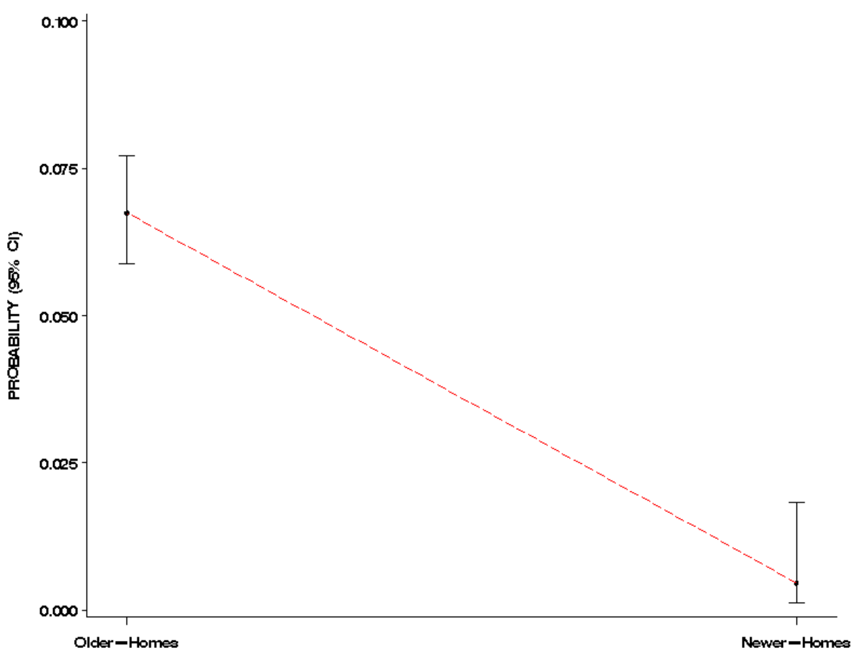


Figure 9. Probability of Arsenic samples exceeding 95 ppm in older and newer homes. Error bars represent 95% confidence limits. Newer homes are those built since 1963 (≤ 42 years old), whereas older homes are those built prior to 1963 (> 42 years old).

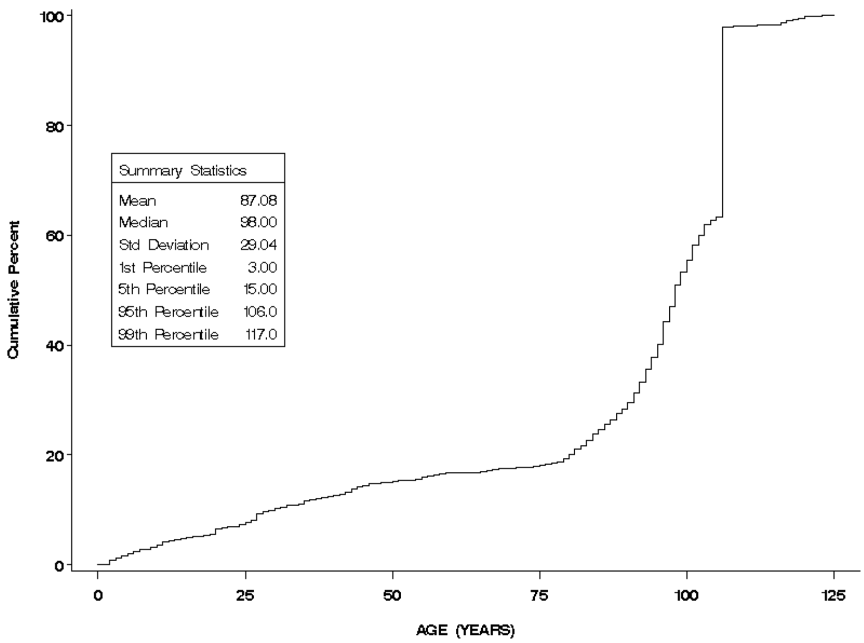
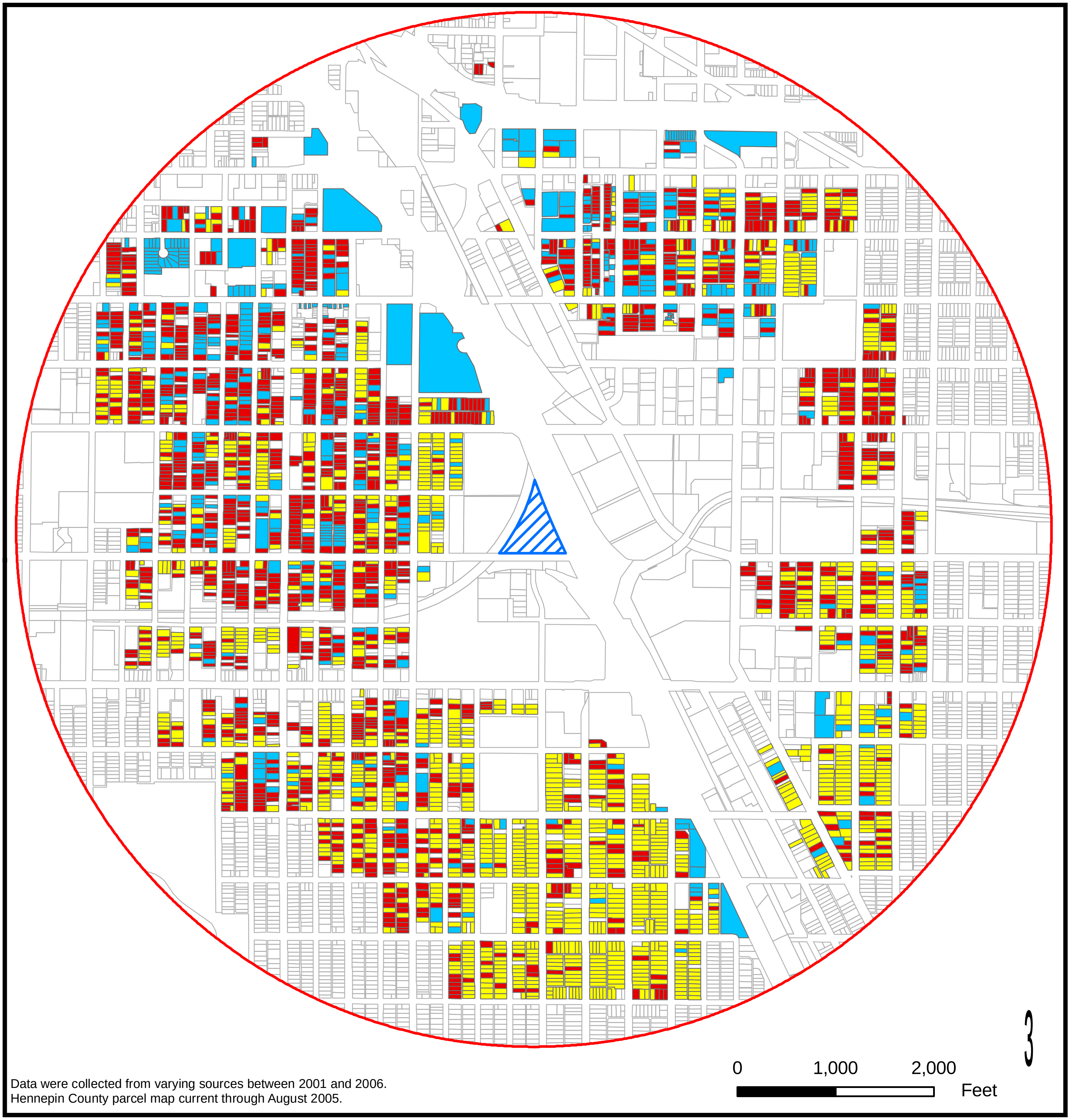


Figure 10. Cumulative Distribution Function (CDF) for houing ages in the residential properties sampled surrounding the CMC site (N = 3,313).



SOUTH MINNEAPOLIS SOIL CONTAMINATION SITE

Minneapolis, Minnesota
Sampled Residential Properties (N = 3,313).

HOUSING AGE (YEARS)

- > 100 yr.
- 43 - 99 yr.
- 0 - 42 yr.

- 1 Mile Radius
- CMC Site
- Hennepin County Properties

Figure Number: 11