Creating a Model that Assesses the Probability of Impact of Petroleum Contaminated Leaksites on Community Wells: Rochester, Minnesota

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Abstract

An analysis of the Rochester areas was conducted in order to understand which community wells were the most vulnerable to contamination from petroleum sources. Analysis involved the development of five modules: Leaksite Proximity to Community Wells, Groundwater Flow Direction, Pollution Sensitivity of Leaksite Locations, Community Well Characteristics, and Leaksite Conditions. Each of these modules were scored on independent criteria and were then multiplied times each other to obtain the final results. In addition to obtaining a community well vulnerability reading, other information was gained from the study by using different modules in different combinations. Combining the first three modules provide a predictive way to look at areas of the community that are likely to remain problematic and might be considered for special zoning. A quick assessment of the possible impact of a new leak, spill, or point source can be obtained by looking at their locations on a grid of the values obtained by combining the first four modules. Combining the first three modules and the fifth can serve to guide new well placement, pumping rates for new wells and well testing. Areas identified with the highest probability of risk for petroleum contamination were found in the central to southern parts of the city. These areas stretch along South Broadway (Highway 63) and about two miles west and one mile east of the intersection of Broadway and Highway 14. Areas to the north and west presented the least amount of risk.

Introduction

Petroleum contamination remains one of the primary source of groundwater pollution in the United States (EPA, 1994). The State of Minnesota has over 13,000 leaky underground storage tank sites with almost 250 in Olmsted County and 182 in the city of Rochester (MPCA, 2000). These areas of demonstrated petroleum releases often lie close to community wells and can negatively affect the quality of the water from these wells (Figure 1).

There is a great need for developing a scientific method for evaluating the potential impact of leaky underground storage tank sites on community wells. In the past, clean-up practices did not include consideration of the leaksite's relationship to wellhead protection areas. The project, " Creating a Model that Assesses the Probability of Impact of Petroleum Contaminated Leaksites on Community Wells: Rochester, MN " was begun in June of 1999 for that purpose. This model was designed in order to give the project manager and community planner a consistent method of evaluating risk when considering the impact of an individual or a group of leaksites on a community well.

This paper introduces the problem, defines terms necessary to understand the study, outlines the components of the study, and describes the process and methods used in the analyses. Additionally, this paper suggests ways in which this model can be used locally for community water planning and commercial zoning or on a statewide basis by the Minnesota Pollution Control Agency (MPCA) for leaksite prioritization and spill management.

Components of the Study

This study consisted of creating a model that considered the interaction between five separate modules:

1) Leaksite Proximity to MunicipalWells (P),
2) Influence of Groundwater Flow Direction (GW),
3) Pollution Sensitivity of Leaksite Location (PS),
4) Community Well Contamination Potential (CW),
5) Leaksite Contamination Potential (LS).

In the past, this type of geographic information was obtained by overlaying several plastic sheets with hand-drawn polygons and creating new maps from them. Modern geographic analysis consists primarily of giving numeric values to these polygon locations and using some type of mathematical process to define their new relationship. Table 1 lists each of the five modules and states their range of factors.

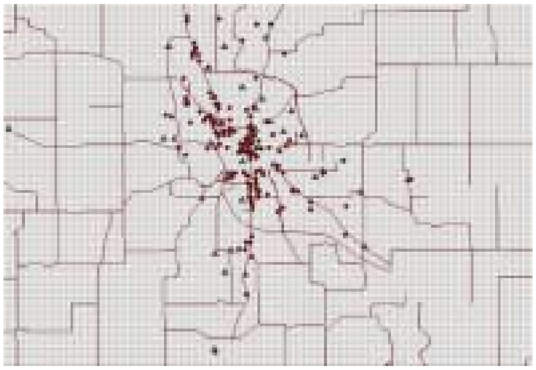
Figure 1. Leaksites (circles) and community wells (triangles) in Rochester, MN

Many researchers have used numeric values to represent physical phenomenon (Burman, 1995; Falteisek, 1991; Olsen and Hobbs, 1988; Porcher, 1989; Trojan, 1986). The values used in this study were arrived at through consideration of this body of research as well as through discussions with hydrogeologists, MPCA project managers, and scientists at the Minnesota Department of Health (MDH) and the United States Geological Survey (USGS). These values will be taken up in greater detail in the evaluation of each module.

Software and Hardware Requirements

Creating and applying this model required using a wide variety of software and hardware at different phases of the project. Hardware included using the Trimble Geo Explorer for Global Positioning Systems (GPS) and making differential corrections to this data with

Table 1. Modules and their range of factors.

Module Abbreviation	Module Name	Range of Factors
P	Leaksite Proximity to Community Wells	1 ⇒32
GW	Influence of Groundwater Flow Direction	1 ⇒ 5
PS	Pollution Sensitivity of Leaksite Location	0.25⇒ 40
CW	Community Well Contamination Potential	1 ⇒ 10
LS	Leaksite Contamination Potential	0.045 ⇒105

Pathfinder 2.01 software. Arcview 3.2, Arcview scripts and Spatial Analyst were used for understanding and geo-processing much of the data. Microsoft Word was used for word processing, and Microsoft Excel was used to calculate the impact of different modules. The MPCA's Oracle Data Base was used to obtain the necessary data on petroleum leaksites. Data from the MDH was accessible in attribute tables from Arc shape files. Netscape Communicator was used to download files and PKunzip was used to make those files useable. Additionally, Microsoft Exchange was used constantly as a means of communication for people involved in this project.

Procedure

Analysis involved the following sequence (details will be added in the next two sections: "Individual Modules" and "Interaction of Modules."

1) Gather all available data including roads, surface water bodies, county boundaries, geological coverages, parcel data, leaksites, and well locations.
2) Re-project all data into the Universal Transverse Mercator Projection using the North American Datum - 1983 (UTM - NAD83).
3) Using GPS, gather all remaining leaksite locations. Differentially correct these using Pathfinder software, then join them to the leaksite coverage.
4) Buffer all wells to a distance of 3200 meters in increments of 100 meters. Record all distances from community wells.
5) Convert those distances into proximity values (P).
6) Create a digitized groundwater flow direction map of Olmsted County.
7) Use this map to determine the groundwater flow direction relationship between each leaksite and all community wells within 3200 meters. Record this as the groundwater flow direction value (GW).
8) Buffer all leaksites to 100 meters. Intersect this buffer coverage with the pollution sensitivity map. Using statistics and a factor determine the pollution sensitivity value (PS) for each leaksite and record it.
9) Create a method of evaluating risk for wells that utilizes the method developed by the Minnesota Department of Health (MDH, 1998). Calculate a risk factor (Community Well Contamination Potential) for

every community well near the city of Rochester (CW).

10) Download appropriate fields from the MPCA database for analysis of individual leaksites.

11) Evaluate every leaksite for risk (Leaksite Contamination Potential) using the fields from step 10 to create the leaksite value (LS).

12) Analyze the relationship between proximity and groundwater flow for each leaksite and community well. Multiply the (P) value (from step 5) times the (GW) value (from step 7) to obtain the (P-GW) value to represent this relationship.

13) Sum all of the values obtained in step 12 for each leaksite to obtain a (P-GW-Tleak) value for each leaksite.

14) Sum all of the values obtained in step 12 for each community well to obtain a (P-GW-Twell) value for each community well.

15) Multiply the (P-GW) value for each leaksite (step 12) by the (PS) value (step 8) to obtain a (P-GW-PS) value to represent the relationship between proximity, groundwater flow direction and pollution sensitivity for each leaksite in relation to each community well.

16) Sum all of the values obtained in step 15 for each leaksite to obtain a (P -GW -PS-Tleak) value for each leaksite.

17) Sum all of the values obtained in step 15 for each community well to obtain a (P-GW-PS-Twell) value for each community well.

18) Multiply the (P-GW-PS) value for each leaksite (step 15) by the (CW) value (step 9) to obtain a (P-GW-PS-CW) value to represent the relationship between proximity, groundwater flow direction, pollution sensitivity, and community well characteristics for each leaksite in relation to each community well.

19) Sum all of the values obtained in step 18 for each leaksite to obtain a (P-GW-PS-CW-Tleak) value for each leaksite.

20) Sum the values obtained in step 18 for each community well to obtain a (P-GW-PS-CW-Twell) value for each community well.

21) Multiply the (P-GW-PS) value for each leaksite (step 15) by the (LS) value (step 11) to obtain a (P-GW-PS-LS) value to represent the relationship between proximity, groundwater flow direction, pollution sensitivity, and leaksite contamination potential for each leaksite in relation to each community well.

22) Sum all of the values obtained in step 21 for each leaksite to obtain a (P-GW-PS-LS-Tleak) value for each leaksite.

23) Sum the values obtained in step 21 for each community well to obtain a (P-GW-PS-LS-Twell) value for each community well.

24) Multiply the (P-GW-PS-CW) value for each leaksite (step 18) by the (LS) value (step 11) to obtain a (P-GW-PS-CW-LS) value to represent the relationship between proximity, groundwater flow direction, pollution sensitivity, community well characteristics and leaksite characteristics for each leaksite

in relation to each community well.

25) Sum all of the values obtained in step 21 for each leaksite to obtain a (P-GW-PS-CW-LS-Tleak) value for each leaksite.

26) Sum all of the values obtained in step 21 for each community well to obtain a (P-GW-PS-CW-LS-Twell) value for each community well.

27) Create views and display information and values on maps.

28) Create map layouts of these and other views and print them.

The first three steps of this project needed to be completed before analysis could take place. Minnesota State agencies are required to work in the Universal Transverse Mercator (UTM) projection utilizing the North American Datum (1983). All data obtained from the Department of Natural Resources (DNR, 1998), the Department of Transportation (DOT, 1996) and the Minnesota Department of Health (MDH, 1999) met this requirement. Leaksite coverages for most of Olmsted County through 1997 were obtained from Rochester Public Utilities. These points needed to be re-projected from the County Coordinate system. The Rochester Planning Department provided pollution sensitivity as well as soil coverages that also needed to be converted into UTM- NAD83. All additional leaksites were geo-positioned using GPS technology and utilizing the same projection and datum.

The remaining analytical steps in this process have been divided into two major sections. The first, "Individual Modules," covers steps 4 - 11. Steps 12 through 26 are discussed in the section "Interaction of Modules."

Individual Modules

Each of the modules will be considered separately and sequentially in the order mentioned above. Modules will be broken down into components and each component will be assessed for how it affects the value of the individual module. The goal of this process is to balance the many influences that define the probability of contamination. A rationale for these values explains how those persons involved in this process defined their concept of balance.

Individual Modules: Module I - Site Proximity (P)

The MDH has recommended that areas should be considered for wellhead protection that fall within two miles (3200 meters) of community wells (MDH, 1992). Each leaksite, therefore, was buffered to this distance in increments of 100 meters. Figure 2 demonstrates the buffering of Leaksite #12272 in Rochester, MN.

The following formula was used to obtain the Proximity value for a single leaksite with all community wells within

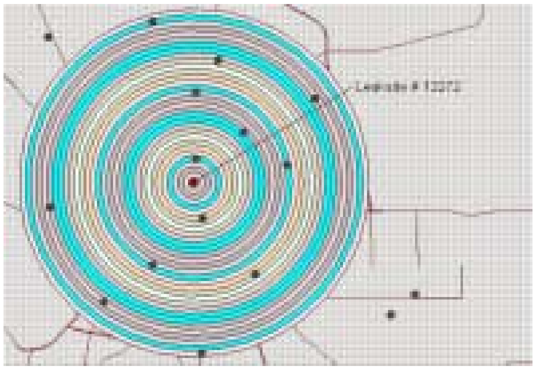

Figure 2. Proximity Analysis, the buffering of Leaksite #12272. Community wells are seen as points around the central leaksite location. Rochester, MN.

3200 meters:

P = 32 - [Truncate (Distance from Community Well / 100)]

$$\sum (P_1 \ldots P_n)$$

The total Proximity value for each leaksite was obtained by summing the values for all community wells within 3200 meters of the leaksite. Some sites in Rochester had as many as eleven community wells within this distance and those values were totaled. The leaksites with the highest proximity values were #5019 and #1290. Each scored 172. Table 2 shows how Leaksite #12272 was scored for proximity.

Rationale for proximity value

The lowest possible proximity value for any leaksite was zero. This value could only be obtained if no community wells were located within 3200 meters from the leaksite location. Table 3 lists a variety of combinations that seemed equivalent.

Table 2. Demonstration of Proximity Analysis for Leaksite #12272

Well #	Distance	Value
1435	<1700meters	16
1436	<500m	28
1437	<1700m	16
1440	<2400m	9
1441	<2700m	6
1442	<3200m	1
1443	<700m	26
1446	<2100m	12
1447	<3100m	2
1448	<2800m	5
1450	<1800m	15
1453	<1300m	20
1455	<2800m	5
Total		**161**

Individual Modules: Module II – Groundwater Flow Direction (GW)

Groundwater flow direction has a tremendous impact on whether or not petroleum products in groundwater will ever reach a community well. Regional groundwater flow direction can, however, be dramatically different than actual site conditions. Karst regions such as the Rochester area can create even more complex problems. For the sake of the simplicity of this study, and because we are considering the region-scale 3200 meter buffer zone around the well, local site conditions have been ignored.

No digitized map of groundwater flow directions for Olmsted County existed so one had to be created from a paper map obtained from the United States Geological Survey (Olsen and Hobbs, 1988). Using this map as a guide, a vector coverage, figure 3, was created using on-screen digitizing in Arcview and giving groundwater flow direction attributes to the resultant polygons.

A community well downgradient from a leaking underground storage tank is much more likely to become contaminated from this petroleum source than an upgradient well. Values were developed to represent this relationship. A triangle was used to view each well to see if it fell within an area 22 1/2° on either side of a line connecting the leaksite to the community well. If a community well fell within that zone, it was considered directly downgradient and was given a (GW) value of five. If a community well was downgradient from the leaksite but fell outside the triangle, it was considered peripherally downgradient and was given a factor of three. All wells upgradient of leaksites were given a value of one. Figure 4 demonstrates the relationship between Leaksite #1173 and Community Wells #1435, #1448 and #1442. Community Well #1448 is directly downgradient and receives a value of five. Well #1435 is peripherally downgradient and receives a value of three. #1442 has no groundwater connection to this leaksite, thus receives a value of one.

Rationale for Groundwater Flow Direction Values (GW)

Groundwater flow direction is extremely important in determining whether or not contaminants from a leaksite or point source will ever reach a community well. It is difficult to make an assessment of this value in isolation, however. A series of equivalent relationships were developed but involved the interaction of proximity and groundwater. This groundwater value is explored more thoroughly in “Interaction of the Modules.”

Table 3. Equivalent Leaksite Values Based on Proximity

Scenario #	Number of leaksites	Distance(s)	Calculation	Value
1	32	<3200 m	(1 X 32)	32
2	1	< 100 m	(32 X 1)	32
3	4	< 2500 m	(4 X 8)	32
4	2	< 1600 m	(2 X 16)	32
5	1	< 1200 m	(1 X 21) +	
	1	< 2200 m	(1 X 11)	32

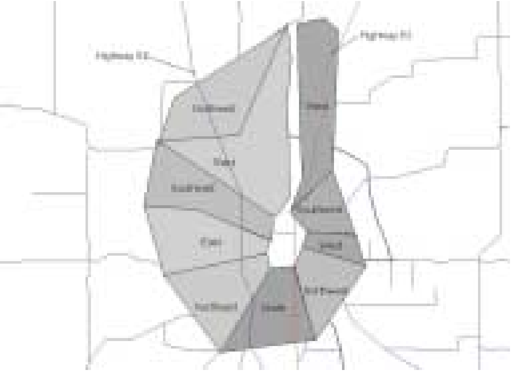

Figure 3: Regional groundwater flow direction in the Rochester area.

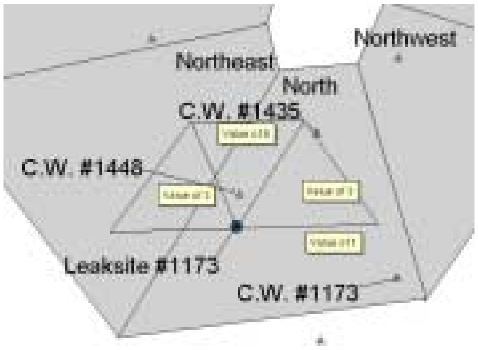

Figure 4. Analysis of the relationship between Leaksite #1173 and Community Wells # 1448, # 1435 and # 1442.

Individual Modules: Module III – Pollution Sensitivity (PS)

Pollution sensitivity is a classification based on the likelihood of surface contamination escaping into deeper aquifers. Pollution sensitivity is basically a measure of the surficial geology in combination with the type of and depth to bedrock. Areas where surficial materials consist largely of highly permeable sands will have a higher potential for transmitting polluted surface water to deeper aquifers. The depth to bedrock is important because surficial material acts as a filter to remove contaminants. Greater depths reduces the risk of lower aquifer problems. The final consideration is bedrock geology. An area containing confining layers of shale or shaley material will slow vertical groundwater movement considerably. These three considerations, surficial geology, depth-to-bedrock and bedrock geology have been combined to define pollution sensitivity as a range of a given geographic location's probability to pollute: very low to very high. Table 4 lists numeric values used to define these differences.

Table 4. Pollution Sensitivity Ratings used for this study.

Pollution Sensitivity Description	Value
Very Low	0.25
Low	1
Low-Medium	5
Medium	10
High-Medium	15
High	25
Very High	40

The original pollution sensitivity map for the State of Minnesota was created by the Geologic Sensitivity Workgroup and was completed in 1991 (Falteisek, 1991). Fortunately, a pollution sensitivity map of Olmsted County had been digitized by the Olmsted County Planning Department and was available for use in this study (Olmsted County Planning, 1992). The map was converted to UTM - NAD83 and was sub-selected to cover the city of Rochester.

Each leaksite was buffered to 100 meters (7.7 acres) and was then joined to the pollution sensitivity map. Statistics were then compiled on these buffered areas to determine what percentage of each rating was attributable to the site. Many sites were located totally within one pollution sensitivity rating area and received the full value for that area. Other sites ended up in several classifications and were pro-rated. Figure 5 demonstrates how several leaksites were categorized for pollution sensitivity. The entire 7.7 acre area surrounding leaksite #10026 had a pollution sensitivity rating of High, and it was given a value of 25. Leaksite #12291 was located in an area classified as 16% High-Medium and 84% High. The pollution sensitivity value for this leaksite would be calculated as (.84 X 25) + (.16 X 20) = 21 + 3.2 = 24 (rounded off).

Rationale for Pollution Sensitivity Values

This model considers the Pollution Sensitivity Index to carry a high rate of influence. It should be remembered that if contamination cannot get off of a site it cannot be carried to a community well; however, if the site is highly permeable, groundwater impacts have been measured in hours. Sites in karst areas are highly unpredictable, and it is assumed that surface contaminants will readily enter the groundwater system. Therefore, a classification design emerged in which the most sensitive areas seemed about 160 times

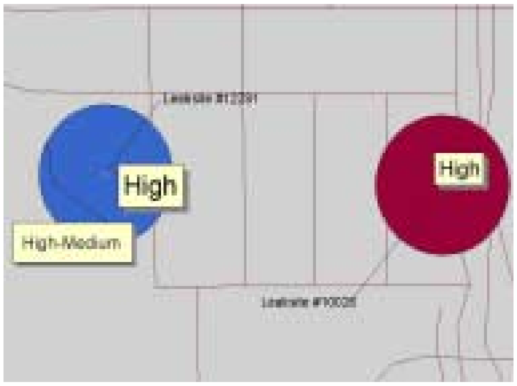

Figure 5. Pollution Sensitivity Values for Leaksite # 12291 and #10026.

more likely to pollute groundwater than areas of low sensitivity: Very High Value = 40; Very Low Value = 0.25; 40 / 0.25 = 160.

Individual Modules: Module IV - Community Well Contamination Potential Factor (CW)

The fourth module to be considered in this study was the Community Well Contamination Potential (CW). The MDH devised a method of analysis that classifies each community well as vulnerable or not vulnerable (MDH, 1998). For the purposes of this study, it seemed necessary to define the likelihood of contamination due to well factors with a broader stroke. For example, due to the pollution sensitivity of wells in the Rochester area, all of them would be classified as vulnerable under the MDH classification. While this may be true, it still seemed necessary to distinguish wells in the area that were *more* likely to become contaminated.

Since the MDH had already done an extensive analysis of each well. These data were used for this study but in a slightly different way. Each well was considered for three variables:

1) Presence of volatile organic compounds (VOC), pesticides or excess nitrates in the well.
2) Pollution sensitivity values for the well site.
3) Consideration of well characteristics + low levels of nitrates.

Each of these variables were summed together to obtain a well value. Well values in this study area ranged from a low of 0.4 to a high of 2.75.

If a site showed either the presence of VOCs, pesticides or nitrate-nitrogen results >10ppm, its first factor was rated as 0.75. If two of these contaminants were found in the water it was rated as 1.0. No well was found that had all three contaminants present. If neither VOCs nor pesticides were found in the water, and it showed nitrate-nitrogen levels < 10ppm, it was given a zero for the first variable.

Calculating the second variable involved determining the pollution sensitivity for the well location. If this value was either high or very high, the well was given a score of one. If the well showed a value of High Medium, it was given a value of 0.5. A value of Medium was given a score of 0.4 while a Low Medium was given a score of 0.3. A Low rating was given a score of 0.2.

The final factor added up well construction values that had already been calculated by the MDH (MDH, 1998). These values included assessments for the pumping rate, lower levels of nitrate-nitrogen, and well construction. MDH values for the third variable were multiplied by 0.2.

The total well value for each community well was calculated by adding up the three factors mentioned above. Table 5 lists the total value of these variables and then distributes them in a range from one to ten.

Table 5. Creation of Well Values (CW)

Range of Variables			Well Value
0.0	⇒	0.5	1
0.5	⇒	0.75	2
0.75	⇒	1.0	3
1.0	⇒	1.25	4
1.25	⇒	1.5	5
1.5	⇒	1.75	6
1.75	⇒	2.0	8
Above 2.0			10

Table 6 demonstrates how the range of variables mentioned in Table 5 can be obtained for actual wells. These variables are also translated into well values.

Table 6. Summation of Variables to Obtain Well Factors for Leaksites # 1436, 1461, 1435, 1437, 1438, and 1440. Rochester, MN

Well #	Presence of VOCs or Pesticides	Pollution Sensitivity Ratings	Pollution Sensitivity Values	Well Construciton	Total well variable	Well value
1435	0	High	1	0.6	1.6	6
1436	0.75	High	1	0.5	2.25	10
1437	0	High-medium	0.5	0.4	0.9	3
1438	0	High-medium	0.5	1	1.5	6
1440	0	High-medium	0.5	-0.1	0.4	1
1461	0.75	Very high	1	0.5	2.25	10

Rationale for Well Values

The purpose of this study was to understand the *probability of risk from petroleum sources***,** and so it seemed necessary to classify those wells with characteristics that increase this risk. Well values used in this study echoed those developed by the MDH. In their study, any well receiving a total well value of 1.0 was considered vulnerable. Using this scheme, nearly every well in our study area would be classified as vulnerable. An assessment of relative risk would be impossible.

In this study, a total well variable of 1.0 was treated as a factor of three. Wells showing less impact had a factor that ranged from one (no additional impact) to three (vulnerable).

The interaction of each of these variables was not cumulative, however. For instance, a well generally shows the presence of pesticides when either pollution sensitivity values are high or well characteristics are less than favorable. Therefore, combining them both and giving a full value to each would exaggerate the risk. The worst combinations were given an additional value of 3.3. This number times the vulnerability factor of 3 made the highest well value equal to 10 (3.3 X 3).

Individual Modules: Module V - Leaksite Contamination Potential (LS)

The final step in this phase of the analysis involved assessing the impact of the leaksites themselves. Without underground storage tanks leaking petroleum products into the ground, there would be no need for this study or for the groundwater concerns mentioned here. Different leaksites can be dramatically different than others. For instance, Leaksite #753 is closed, had no excavation report done, had no residual contaminated soils and no groundwater impact. A site with high impact is Leaksite #5035. This site is open, has a completed excavation report, has residual soil contamination, has groundwater contamination and shows the presence of free product as well as other factors. The likelihood of contaminating a well in the second scenario is far greater than in the first. Leaksite values need to reflect that difference.

The MPCA database contained enough information to be able to demonstrate the relative risk posed by a leaksite (MPCA, 2000). Site risk information included: status as an open or closed site, whether an excavation report was ever required, whether contaminated soils remained on site after closure, whether a limited or remedial site investigation was required, whether groundwater was impacted, and whether or not free product was present and, if so, to what depth. Table 7 lists each of these components and their values.

The Leaksite Contamination Potential (LS) was calculated by answering each of the questions in Table 7 and obtaining a value for that item. Those values were then multiplied times each other. Table 8 demonstrates this process by evaluating Leaksite #6503 in Rochester. The (LS) for Leaksite #6503 would be 21 (0.3 X 2 X 1 X 1 X 10 X 3.5 X 1).

Rationale for (LS) values

The motivation for developing the (LS) was twofold. First, each of the criteria mentioned in Table 7 needed to be scaled so that these components accurately represented their potential threat. Second, the overall (LS) rating of even the most extreme sites had to reflect the relative balance of all modules.

Table 7. Leaksite components and their values.

Item	Present? Yes	No
Open Site?	1	0.3
Excavation Report?	2	1
Contaminated Soils at closure?	1.5	1
Limited Site Investigation (LSI)?	3	1
Groundwater Impact?	10	1
Remedial Investigation?	3.5	1
Presence of Free Product?	5	1
Free Product Depth		
	< 1 inch	= 1
	> 1 inch	= 2

A number of MPCA project managers were solicited to gain their subjective assessment of risk between the worst possible site and the most innocuous ones. All managers agreed that this difference should be expressed in a three to four magnitude differential. A difference of 3500/1 was selected as optimal.

If the worst site were to be given a factor of 3500, it would distort the impact of a leaksite and make all other modules irrelevant. The highest possible value for module one was 32, for module two, it was 5, module three was forty and module four was 10. In order to decrease the value of the worst leaksite, however, the most innocuous one would have to be less than one. In multiplication, using numbers less than one involves the strange element of having a site actually reduce the overall

Table 8. Leaksite components for Leaksite #6503: Rochester, MN

Item	Present? Yes	No	Value
Open Site?		√	0.3
Excavation Report?	√		2
Contaminated Soils at closure?		√	1
Limited Site Investigation (LSI)?		√	1
Groundwater Impact?	√		10
Remedial Investigation?	√		3.5
Presence of Free Product?		√	1
Free Product Depth			not applicable
		< 1 inch	= 1
		> 1 inch	=2

risk of a location. Obviously, the presence of a leaksite, regardless of how innocuous it was, would not make an area less of a hazard.

It was felt that a site closure actually represented a reduction of risk, therefore, this category was given a value of 0.3. This would represent a 70% reduction in risk for a site designated by project managers as closed. In a hierarchical fashion, other values were developed. Groundwater impact was given a 10 because community wells only become contaminated through impacted groundwater. Free Product was given the second highest value because the presence of floating hydrocarbons on the water table provides a source of contamination for many years. The need for a Remedial Investigation scored 3.5 because it is an indicator of certain risk factors, including surficial geology and bedrock geology. A limited site investigation is similar to a RI, however, the risk factors are lower than in the RI. The presence of an excavation report was given a value of two because the need for an excavation report is an early indicator of the seriousness of a leaksite. Similarly, free product greater than one inch would lengthen the time groundwater is exposed to petroleum products. The presence of contaminated soils at closure was given a value of 1.5 because these soils might still function as a source for groundwater contamination later.

These values were then used to calculate a (PS) value for every leaksite in Rochester, and it was thought that these value were still too high. For instance, the worst leaksite in the area #5856 would have scored a 700. The range of possible values seemed to fit best if an additional value of 0.15 were used. This made the worst site 105 (700 X 0.15) and about 60% of all sites fell below a factor of three.

Interaction of Modules

Combining different modules is the most dynamic way to obtain useful information from this study.

Multiplying the values obtained for each module seemed to allow the greatest amount of flexibility in interpreting the data. For instance, if three modules were evaluated on a multiplier effect of 1 to 5, values could range from 1 (1 X 1 X 1) to 125 (5 X 5 X 5). If these same modules were evaluated on an additive effect, values would range from 3 (1+ 1 + 1) to 15 (5 + 5 + 5). A leaksite scoring highest on one module and lowest on the other two would score (5 X 1 X 1 = 5). This site would be considered low risk (5/125 = 0.04). If these three factors were added together, this site would score (5 + 1 + 1) or 7. The mathematical value for this site would then reflect a more central value (7 / 15 = .47). The former method of calculation seemed the most realistic.

Different combinations of modules were used to obtain different risk values for petroleum contamination. For instance, multiplying all of the factors helps us to understand which community wells are the most at risk. Removing the Community Well Contamination (CW) Potential results in knowing which areas of the community produce the greatest risk *regardless of well type and construction.* Other combinations will be taken up in this section and later in the paper.

Theoretically, the worst individual leaksite interacting with a single well would consist of the five highest values (32, 5, 40, 10, 157.5). When multiplied together this site would score 10,800,000. A site such as this would be located less than 100 meters from a community well which had demonstrated problems with contamination and construction. This leaksite would be found directly upgradient of this well, would be located in sandy soil, and would have demonstrated groundwater contamination as well as the presence of free product floating on top of the water table.

The single worst leaksite / community well relationship in the Rochester area, using the model outlined in this paper, would be Leaksite # 782 which received a score of 914,500 with respect to Community Well #1443. This leaksite is upgradient (5) and < 200 meters from Community Well #1443 (31). This closed site is in an area of high pollution sensitivity (25), had residual soil contamination, and groundwater contamination as well as the presence of free product (LS = 23.6). The character of Well #1443 also contributed to the high rating. It had shown the presence of pesticides at some time, is located in an area of high pollution sensitivity, was poorly constructed and had a high pumping rate (10). (5 X 31 X 25 X 23.6 X 10) = 914,500

Theoretically, the only limit to how high a value could be obtained for a leaksite would be the number of wells within 3200 meters. The total value for each leaksite is the sum of all of the interactions with all of the individual wells within this range. In Rochester, the worst leaksite found was (#5856) with a value of 4,452,000. Eight community wells were found within this range for this site. Further analysis of these values will be taken up later in this paper.

The lowest value for a single leaksite would consist of the five smallest values (1, 1, 0.25, 1, 0.045). When multiplied, the end value of this leaksite would score 0.01125. A leaksite such as this would be located downgradient of a single community well located between 3100 and 3200 meters from the site. Soils would be generally impervious with a great distance to bedrock. The bedrock layers at the site would contain at least one confining shale layer. The community well would be located in a geologically safe area and would have low pumping rates and no demonstrated contamination or problems with well construction. In the Rochester area, the leaksite demonstrating the least impact was #6295 and received a score of 30.

Summarizing data into smaller categories too early in the study was thought unwise because of wanting to represent subtle variations in each module. Rounding these numbers too early might have compounded later errors. After all calculations were made, categories *were then* summarized into areas ranging from "Most Vulnerable" to "Least Vulnerable."

One limitation of this study is that it only utilized sites in the Rochester area and compared them to each other. Considering that much of the Rochester area is located in geologically sensitive areas, it is likely that these numbers are higher than they'd be in many other non-karst locations. Utilizing this model in a number of settings would make it possible to determine how these Rochester sites fit in relation to other locations in the state.

Interaction of Modules: Proximity and Groundwater Flow Direction (P-GW)

The interaction of proximity (Module 1) and groundwater flow direction (Module 2) is a much more accurate assessment of the potential impact of any point source on a community well. P-GW values reflect these relationships and were multiplied together to express an individual leaksite's potential impact on a community well as varying from 1 to 160. A leaksite that was between 3100 and 3200 meters from the well and was downgradient would score a one (1 X 1). A leaksite that was less than 100 meters from a community well and was directly upgradient would score 160 (32 X 5). The total of all of the (P–GW) values for each leaksite / community well relationship within 3200 meters of a single leaksite was defined as the (P-GW-Tleak) value. The total of all of the (P – GW) values for each leaksite / community well relationship within 3200 meters of a single well was defined as the (P-GW-Twell) value.

Table 9 shows how the (P-GW-Tleak) value of 389 was obtained for Leaksite #2172. Obtaining Twell values involved totaling the values for as many as 100 leaksites. Because of the cumbersome nature of presenting this analysis, we will not show how these calculations were made.

Figure 6 displays the top 20% of leaksites in the Rochester area with the highest (P-GW-Tleak) values. We can see that site proximity and groundwater flow direction tend to suggest that the southern and southeastern part of the city are the most problematic. As this study continued, areas of concern became increasingly focused in this area.

Table 9. Calculating the (P-GW-Tleak) value for Leaksite #2172.

Community Well #	Distance (m)	Distance Value	Groundwater Flow Direction	Groundwater Flow Direction Value	Total
1435	<1100	22	Direct	5	110
1436	<2500	8	Direct	5	40
1442	<1000	23	Peripheral	3	69
1443	<1400	19	Direct	5	95
1446	<1000	23	Upgradient	1	23
1448	<1800	15	Upgradient	1	15
1450	<2800	5	Upgradient	1	5
1452	<200	31	Upgradient	1	31
1453	<3200	1	Upgradient	1	1
					389

Table 10. Equivalent Scenarios based on Proximity and Groundwater Flow Direction

Scenario	# of Leaksites	Proximity	Proximity Factor	Groundwater Flow Dir	GW Factor	Calculation	Total
A	1	<100meters	32	Direct	5	(1 X 32 X 5)	160
B	160	<3200meters	1	Upgradient	1	(160 X 1 X 1)	160
C	5	<2200meters	11	Peripheral	3	(5 X 11 X 3)	165

Figure 6. Location of top 25% of leaksites based on (P-GW-Tleak values. Rochester, MN.

Rationale for (P-GW) values

As mentioned in the "Individual Modules: Groundwater Flow Direction" section, it is easier to see the rationale for groundwater values by seeing them in context with proximity values. Table 10 lists a number of these equivalent scenarios.

Interaction of Modules – Proximity, Groundwater Flow Direction and Pollution Sensitivity (P-GW-PS)

By factoring in the pollution sensitivity of the leaksite with the proximity and groundwater flow direction values, we obtain a picture of the permanent vulnerability of certain areas of the community to groundwater contamination from petroleum leaksites.

The three factors thus far considered are fairly stable. For instance, the existence of leaksites will not change substantially, and new leaksites will generally be located along the same commercial corridors. The relationship between groundwater flow and existing community wells will remain fairly constant (although old wells might cease to be used or new ones might be added) and so will the pollution sensitivity classification of the area. Figure 7 displays the top 25% of all leaksites based on their proximity, groundwater flow direction and pollution sensitivity values.

Figure 7. Location of top 25% of leaksites based on (P-GW-PS-Tleak) values. Rochester, MN.

The highest (P-GW-PS-Tleak) value for any leaksite in our study area was obtained for #2172 which had a 9525. This value was obtained for this site by multiplying the (P-GW-Tleak) value of 381 by 25 (High pollution sensitivity). (381 X 25 = 9525).

By summing the (P-GW-PS-) values for each leaksite that lies within 3200 meters of a community well, we can obtain a (P-GW-PS-Twell) value for each community well. These values can then be interpolated and displayed using Spatial Analyst. By overlaying the actual well locations on this display, we can easily see which community wells are located in problematic areas. This new map, Figure 8, while similar to the DNR Pollution Sensitivity map, is extremely useful because it incorporates the dynamic relationship between leaksites and community wells.

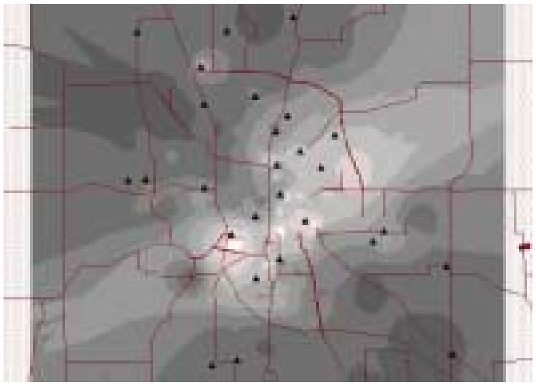

Figure 8. Interpolated map of P-GW-PS-Tleak values with community wells. Rochester, MN

Another interesting thing to note is how many leaksites are impacting each well. For instance, Well #1435 is being impacted, however slightly, by over 100 separate leaksites, while well #1436 is affected by 81. Some of the wells in better locations are only being impacted by a few leaksites: #1425 =1; #1473 = 2; #1472 = 1. Simply on the basis of shear numbers, it is easy to see that the relationship between commercial corridors and community wells is a significant consideration.

Interaction of Modules - Proximity, Groundwater Flow Direction, Pollution Sensitivity, and Community Well Values (P-GW-PS-CW)

Combining the community well factor described earlier with the values found from the previous section, and again looking at them from the point of view of the leaksite and the well, we obtain several useful data sets. The first data set, (P-GW-PS-CW-Tleak), extends the values obtained in the previous section by looking at how each of the individual well values either magnifies or lessens the impact of the leaksite. The calculation for the second data set, (P-GW-PS-CW-Twell) is shown in Table 11. This data set operates with the community well at the center and allows us to understand how each leaksite affects it. Each of these values can be used for similar purposes: identification of high-risk areas in the community.

These values give us a long-term view of areas of the community that are highly vulnerable to current and future pollution sources. This kind of information should be able to guide consideration for future well placement and zoning based on wellhead protection. It should help the MPCA in determining whether the clean-up of an emergency spill should be given a higher than normal priority. Figure 9 shows how the petroleum release program project manager could use this information to know which new leaksites are located in areas much more likely to contaminate community wells.

Interaction of Modules - Proximity, Groundwater Flow Direction, Pollution Sensitivity, Community Well Characteristics and Leaksite Conditions (P-GW-PS-CW-LS)

The final step in this analysis was to factor the leaksite values obtained above. This last process allows us to understand which leaksites pose the most risk to community wells and which wells are the most at risk for petroleum contamination. Figure 10 interpolates this information throughout the Rochester area allowing us to understand which areas of the community are most likely to have wells become contaminated. This interpolation has its greatest value as a measure of *present threat* to community wells.

Table 11 – Calculating a Twell value for Community Well # 1444 (Based on Proximity, Groundwater Flow Direction, Pollution Sensitivity and Community Well Characteristics)

Leaksite #	(P -GW)	PS	CW	Total
234	6	25	1	150
723	23	25	1	575
2953	95	12	1	1140
4053	6	25	1	150
4151	8	25	1	200
5483	11	25	1	275
5682	5	25	1	125
5868	11	25	1	275
7388	16	25	1	400
7782	6	25	1	.150
7878	12	25	1	.300
8445	30	24	1	720
9485	6	25	1	150
10747	10	15	1	150
10987	18	25	1	450
11164	13	25	1	325
11485	150	15	1	2250
Grand Total				**7785**

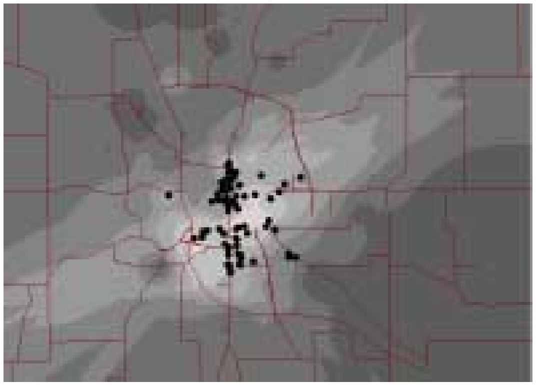

Figure 9. Leaksites located in areas where they are most likely to contaminate community wells. Rochester: MN

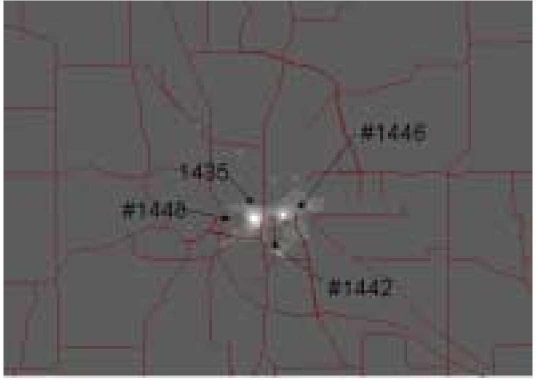

Figure 10. Wells most likely to become contaminated from leaksites. Rochester, MN.

Uses of the Model

This model should be useful to persons involved in a wide variety of groundwater protection activities. Most of these applications have been mentioned in the descriptions of Modules in earlier sections, however, a general summary seems useful.

I. Proximity (P)

Identifies locations in a community where leaksites are present. Areas of high density should also identify where commercial and industrial point sources are also concentrated.

II. Groundwater Flow Direction (GW)-

Regardless of using this full analysis, a digitized groundwater flow direction map is extremely useful for Emergency Response, community planning, and leaksite risk management.

III. Pollution Sensitivity (PS)-

This module is most useful in combination with the proximity and groundwater flow direction modules. Without doing this entire analysis, knowing the pollution sensitivity of the location of a leaksite should be helpful in assessing site risk.

IV. Community Well Contamination Potential (CW) -

Very similar to one already created by the MDH; however, this module can help to assess which wells are at greater risk for contamination.

V. Leaksite Contamination Potential (LS)

Helps the MPCA project manager to look at a site and get an immediate assessment of the risk the site poses.

VI. Proximity-Groundwater Flow Direction (P-GW)

Identifies areas of a community in which leaksites and point sources are more likely to present problems.

VII. Proximity-Groundwater Flow Direction-Pollution Sensitivity (P-GW-PS)

This combination should be able to clearly define areas within the P-GW matrix from Step VI above that are particularly problematic. This module could be useful in guiding zoning considerations that will minimize the possibility of impacts to community wells.

VIII. Proximity-Groundwater Flow Direction-Pollution Sensitivity-Community Well Contamination Potential (P-GW-PS-CW)

This module gives us a *current* snapshot of the community based on the present configuration of community wells. This module can help recognize which community wells are inherently more risky. It can guide pumping rates, shutting down of old wells and general well management. It is also an extremely useful guide for Emergency Response situations in determining if a spill might pose a greater than average risk of contaminating community wells.

IX. Proximity-Groundwater Flow Direction-Pollution Sensitivity-Leaksite Contamination Potential (P-GW-PS-LS)

Identifies the areas of a community that are particularly vulnerable to groundwater contamination due to petroleum sources. This module can be used to guide new well placement.

X. Proximity-Groundwater Flow Direction-Pollution Sensitivity-Community Well Contamination Potential-Leaksite Contamination Potential- (P-GW-PS-CW-LS)

This combination provides an overall assessment of which community wells are at greatest risk for petroleum contamination as well as which leaksites are most at risk to cause these problems. These considerations can guide well pumping rates, well closure, and leaksite clean-up prioritization.

Uncertainties of the Model

This model has a variety of uncertainties that should be understood when attempting to apply it in a given location. The overall goal of this project was to identify the general location of probable problems. In general, an attempt was made to balance each of the five modules so that all were fairly represented and were not overwhelmed by any other. The factors that were used within each module were also balanced so that no single factor dominated.

Uncertainties enter into the model during the development of each module. These uncertainties arise because of positional error, groundwater flow delineations and other problems associated with data and GIS coverages. This section will deal with each of these uncertainties.

I. Location of Leaksites

Ideally, leaksites in the Rochester would have been geo-located at the tank basins because this is the source of petroleum contamination. GPS readings were not always taken at the tank basins, however, because most of these locations had canopies over them to protect customers from inclement weather. These points were usually taken less than ten meters from the actual source. Other problems occurred in areas that were no longer used as gas stations. Some of these sites had been paved over for new buildings or parking lots and finding the exact location of the original tank basin was impossible. Actual site locations were probably never more than twenty five meters from the GPS measured location.

II. Location of Community Wells

Community wells were geo-located by the MDH using geo-coding. Certain errors may have occurred in the placement of these wells. They were not re-checked but are assumed to be correct.

III. Leaksite Proximity to Community Wells

Assuming minimum geo-locational errors for leaksites and community wells (see above), site proximity values are probably quite accurate. Each leaksite was buffered to 3200 meters in Arcview. These buffers made it easy to identify the actual distances between wells and leaksites.

IV. Groundwater Flow Direction

Any attempt to treat groundwater flow direction as absolute would result in disappointment. Groundwater volume was ignored although it probably had some impact. Groundwater flow direction values used in this study were based on the USGS map of Olmsted County created in 1988. This map was very generalized and contained less than 500 data points for the entire county. Undoubtedly, specific areas could be different due to long-term environmental changes. The digitized map made for this study was a compromise. It involved defining large polygonal regions as one of eight directions. Necessarily, some of these boundary areas were subjective. Using an overlay to define groundwater flow direction introduced additional errors due to the subjectivity of these boundary regions.

V. Pollution Sensitivity Map

Pollution sensitivity maps were created in the late 1980s and were often based on minimal geological information. These maps are generally accepted as adequate even though they are not site-specific. MPCA project managers often find that actual sites can be quite different. It was beyond the scope of this paper, however, to look at the site conditions for all leaksites and community wells. The USGS map was digitized by the Olmsted County planning office and additional errors were probably introduced at that time. Considering that most areas in Rochester were defined as medium-high or high, it is unlikely that these errors were significant in the overall analysis.

VI. Community Well Contamination Potential

The values used for this module were developed by staff at the MDH. It is impossible to vouch for the accuracy or inaccuracy of this data.

VII. Leaksite Contamination Potential

The information on the MPCA database is generally accurate although errors have been found in the past. Older leaksites are sometimes problematic because some of the reporting and defining values in the past were different than they are now. The remarks screen for each leaksite was used to collaborate information found on the database.

VIII. General Data Entry Errors

This study involved data entry of over 15,000 points. Undoubtedly, certain errors in recording information crept into the study. It seems doubtful that the occasional data error would skew the results. More significant errors might have occurred when values were obtained from complex formulas. This project was tested repeatedly for these larger "system errors" and none seem to exist.

Requirements for a Broader Application of the Model

This model can be applied to leaksite and community well management. Any community in which it was to be applied would require extensive background preparation in order to obtain satisfactory results. The principal reason for developing this model was so that the individual project manager at a petroleum release site would be able to get a scientific evaluation of the potential for risk to a community well from a given leaksite. Project managers cannot be expected to spend hundreds of hours to obtain this information. In order to minimize this effort a processing method similar to the one done in this study would need to be prepared for each community/ county by a Principal Analyst (PA). An application could be developed where the MPCA project manager as the end-user could gain valuable information about an old or new leaksite with the push of a few buttons on a customized GIS interface.

Consideration of the Role of the Principal Analyst (PA)

The PA needs to work with a wide variety of data and processes to make this information readily available for the end-user. The PA should be a conduit for information from a variety of sources and must bring that information into a simplified format. The role of the PA will center on three primary areas. First, s/he must work with different state agencies to understand, create and maintain data necessary for the analysis. Second, the PA needs to create a simplified process so that a county-by-county analysis can be done that will provide the background needed for the end-user. Finally, the PA needs to organize the data and processes so that the end-user can succeed in obtaining the desired results.

The PA must be able to work with the MPCA, MDH and with local water planners in conducting successful data management. The PA must make sure that leaksite data from the MPCA necessary for this analysis is easily available. The PA must be able to digitize county groundwater coverages if they are lacking and s/he probably needs to work with local units of government and the state to see that all of the geological information is in digital form. The PA needs to be kept aware of changes in community wells i.e., new wells, changed pumping rates, wells taken out of service, etc. and be able to readily incorporate those changes into an updated manipulatible data base.

The PA must perform the analysis done on Olmsted County on other counties where the geologic and hydrogeologic data are available. This will require the PA to find simple script driven means of allowing the different data bases (MPCA petroleum release program, MDH and Arcview) to talk to each other, thereby, automating as much of the analysis as possible. This background step will allow for the end-user, whether petroleum release program project manager or community planner, to access information without spending inordinate amounts of time obtaining it.

The third most important step is for the PA to create a user interface that allows the end-user to gain information easily. The PA would need to work in Arcview associating scripts with buttons that would make it easy for the end-user to gain information about the individual leaksites, the nearest community wells, groundwater flow direction, site conditions such as pollution sensitivity, and whatever other information would be helpful.

The ability to create a picture of community petroleum impacts cannot be easily accomplished in all areas. Fortunately, MDH has a complete analysis of all well locations (Module 4) and the MPCA has adequate data available from their leaksite database to readily assess the proximity, and leaksite values (Module 1 and Module 5). Many counties do not have completed geological atlases, making groundwater flow direction difficult to ascertain

(Module 2). In some locations, groundwater data exists but has not been digitized and preparing this information for processing could take hundreds of hours. Many counties also lack digitized pollution sensitivity information (Module 3) and this could cause delays similar to processing Module 2. If the political will is available to offer enough support, these efforts should be able to be accomplished.

Conclusion

This paper outlines a method of assessing the relationship between petroleum- contaminated leaksites and community wells in Rochester, MN. It offers a variety of ways of looking at five modules: leaksite proximity, groundwater flow direction, pollution sensitivity, community well contamination potential and leaksite contamination potential. Each of these modules was given a representative sphere of influence. Modules were then combined to obtain different information.

This study found that community wells in the central and southern parts of the city were at the greatest risk for experiencing petroleum contamination. These areas were identified because of the combination of leaksites near community wells, the groundwater flow direction in these relationships, the generally sandy soils at these leaksites, high ratings for community well problems as well as the riskier nature of the leaksites themselves.

This study should be able to assist leaksite and community well managers, as well as guiding the city of Rochester in some of its land use and zoning. Professionals can be guided in their decision making by understanding how different information can be obtained by different combinations of modules.

This type of study could be done for many more communities but would require extensive work to prepare it. Smaller communities with few leaksites and municipal wells would require minimal effort while larger cities would require much more time.

One must act cautiously before drawing unwarranted conclusions from this study. It would be easy to conclude that serious problems are present, even if they are not. This study provides an assessment of *greatest risk; however, it does not imply that petroleum contamination has or will occur in a given location.* For instance, In the city of Rochester, no petroleum volatile organic compounds have ever been found in community wells that exceeded the Health Risk Limits recommended by the MDH (RPU, 2000). This study is an attempt at helping communities like Rochester make sure they never will.

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