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A MULTI-LEVEL ASSESSMENT METHODOLOGY FOR DETERMINING THE POTENTIAL FOR GROUNDWATER CONTAMINATION BY PESTICIDES

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Environmental Monitoring and Assessment

MANAGEMENT PERSPECTIVE

Numerous studies have documented the widespread occurrence of groundwater contamination by pesticides in agricultural areas throughout Canada. The contamination of Canada's groundwater by pesticides has occurred in spite of government regulations and the use of pesticides within recommended applications guidelines. Although extensive field testing of the leaching and persistence characteristics of pesticides is required prior to regulatory approval (Pesticide Registration Review 1990), it is neither feasible nor possible to assess every conceivable agricultural setting in which the pesticide would be used. Nor can post–approval monitoring be undertaken everywhere to ensure that the quality of groundwater in agricultural areas is sustained.

In order to assist regulatory personnel with their assessments of the potential impact of pesticides on groundwaters in agricultural regions throughout Canada, a multi–level pesticide assessment methodology has been developed to permit regulatory personnel to undertake a variety of assessments on the potential for pesticide used in agricultural areas to contaminate the groundwater regime at an increasingly detailed geographical scale of investigation. This assessment methodology is discussed in this paper. The assessment methodology is combines GIS, extensive databases, data management systems, expert systems, and numerically-based pesticide assessment models, to form an environmental information system for assessing the potential for pesticides to contaminate groundwater. A multi–level approach accounts for a variety of assessment objectives and detail required in the assessment, the restrictions on the availability and accuracy of data, the time available to undertake the assessment, and the expertise of the decision maker.

ABSTRACT

A multi–level pesticide assessment methodology has been developed to permit regulatory personnel to undertake a variety of assessments on the potential for pesticide used in agricultural areas to contaminate the groundwater regime at an increasingly detailed geographical scale of investigation. A multi–level approach accounts for a variety of assessment objectives and detail required in the assessment, the restrictions on the availability and accuracy of data, the time available to undertake the assessment, and the expertise of the decision maker. The Level 1: regional scale is designed to prioritize districts having a potentially high risk for groundwater contamination from the application of a specific pesticide for a particular crop. The Level 2: local scale is used to identify critical areas for groundwater contamination, at a soil polygon scale, within a district. A Level 3: soil profile scale allows the user to evaluate specific factors influencing pesticide leaching and persistence, and to determine the extent and timing of leaching, through the simulation of the migration of a pesticide within a soil profile. Because of the scale of investigation, limited amount of data required, and qualitative nature of the assessment results, the level 1 and level 2 assessment are designed primarily for quick and broad guidance related to management practices. A level 3 assessment is more complex, requires considerably more data and expertise on the part of the user, and hence is designed to verify the potential for contamination identified during the level 1 or 2 assessment. The system combines environmental modelling, GIS, extensive databases, data management systems, expert systems, and pesticide assessment models, to form an environmental information system for assessing the potential for pesticides to contaminate groundwater.

INTRODUCTION

The contamination of Canada's groundwater by pesticides has occurred in spite of government regulations and the use of pesticides within recommended application guidelines. Although extensive field testing of the leaching and persistence characteristics of pesticides is required prior to regulatory approval (Pesticide Registration Review 1990), it is neither feasible nor possible to assess every conceivable agricultural setting in which the pesticide would be used. Nor can post–approval monitoring be undertaken everywhere to ensure that the quality of groundwater in agricultural areas is maintained. The federal government agencies responsible for groundwater quality assessment, management, and protection have addressed this task by relating the principle factors that influence the mobility and persistence of pesticides in soil and groundwater including, pesticide usage, soil types, agricultural practices, meteorological information, and topographic features. Recent trends involve the coupling of the common practices of field monitoring, data collection and analysis, with Geographical Information Systems (GIS) and predictive modelling.

The potential for a pesticide to leach to the water table, and hence contaminate groundwater, can be assessed with a variety of existing models which range from simple screening models to complex simulation models. At the simplest level, one can estimate the relative mobility and persistence of a pesticide with respect to other pesticides, or the relative potential to which the physical characteristics of a soil profile will affect the extent of contamination with respect to other soil profiles, with a variety of screening models (Laskowski et al. 1982; Jury et al. 1983; Rao et al. 1985; Wilkerson and Kim 1986; Gustafson 1989). At the most comprehensive level, physically–based simulation models (Enfield et al. 1982; Carsel et al. 1984; Nofziger and Hornsby 1986; Wagenet and Hutson 1987; Leonard et al. 1987; Bonazountas and Wagner 1987) enable a user to quantify the distribution and leaching rates of a pesticide in the subsurface with time and depth.

The choice of an assessment model or an assessment technique for evaluating the potential for a pesticide to contaminate groundwater should not be based solely on which model contains the most processes that affect the fate of a pesticide in the subsurface, and in the most comprehensive manner. Rather the choice of an assessment model should depend on the objectives of the assessment, the available data, the expertise of the assessor, and time constraints. For example, if the user is only interested in a relative ranking of the mobility of a set of pesticides, then a simple screening model will perform this task as well as a complex simulation model, but with considerable less data required and time involved. Also, if the data required to undertake a detailed simulation are not available or lacking in accuracy, then the results of a simulation will be no more accurate or meaningful than comparative results from a screening model assessment.

Several assessment methodologies or decision support systems, that combine a pesticide assessment model with GIS, and extensive databases, have been presented for evaluating the potential for groundwater contamination from pesticide usage (Loague et al. 1989; Carsel et al.

1991; Imhoff et al. 1994). However, these assessment methodologies are limited in that they rely on only one assessment model or method, and thus, may lead to problems in that the model may not be appropriate for the assessment objectives, or the data required by the model may not be available. Further the use of only one assessment method may bias the objectives of the assessment or its results. Thus, a decision may be driven by the available information, and not by the goals of the assessment.

The objectives of this study are to the develop a system suitable for assessing the potential for groundwater contamination from pesticides, and to develop the assessment methodology and models such that it can be used by regulatory personnel who may not have expertise in pesticide modelling and assessment. The approach taken here is to combine several pesticide assessment models within one system to account for the variety of assessment objectives and detail required by decision makers, and the availability of information needed to meet the objective of an assessment.

The system developed here combines environmental modelling, GIS, extensive databases, data management systems, knowledge-based systems, and pesticide assessment models, to form an environmental information system for assessing the potential for pesticides to contaminate groundwater. The RAISON (Regional Analysis by Intelligent Systems ON a microcomputer) environmental software (Lam et al. 1991) acts as the basic system for all data storage, management and analysis, as well as integrating all environmental modelling methodologies. It also provides the capability of displaying results and information through its spreadsheet, graphics, and GIS modules. The pesticide assessments are handled with the EXPRES (EXpert system for Pesticide Regulatory Evaluations and Simulations) expert system (Crowe and Mutch 1989; Mutch et al. 1993) which is linked to RAISON. Our assessment system has two major advantages. First, an assessment for the potential for groundwater contamination is based on (1) the best available data, (2) the best scientific principles and tools for assessments, and (3) the best available expert interpretation of the data and assessment results. Second, the assessment results would be consistent with an expert's assessment and would be obtained regardless of the expertise of the user of the system. Hence it provides a rational and consistent basis for the evaluations.

PESTICIDE ASSESSMENT METHODOLOGY

The strategy taken here to assess the potential for pesticides to contaminate groundwater is based on a multi–level evaluation procedure that will account for (1) the variety of assessment objectives and detail required by decision makers, (2) the availability of accurate site and pesticide data required to undertake the assessment, and (3) an increasingly detailed geographical scale of investigation. Accompanying this increase in scale is a more precise and reliable assessment, the use of more comprehensive assessment methodologies and models, and the requirement for substantially more data.

The multi–level approach is undertaken at three geographical scales of investigation (Figure 1). The *Level 1: regional scale* is designed to prioritize districts having a potentially high risk for groundwater contamination from the application of a specific pesticide for a particular crop. The *Level 2: local scale* is used to identify critical areas for groundwater contamination, at a soil polygon scale, within a district. A *Level 3: soil profile scale* allows the user to evaluate specific factors influencing pesticide leaching and persistence, and, to determine the extent and timing of leaching, through the simulation of the migration of a pesticide within a soil profile.

The level 1 and level 2 assessments are more general and qualitative in nature, and hence, these two assessment levels are designed for regulatory guidance such as prioritizing pesticides or sites for detailed analysis of future pesticide monitoring, or evaluating alternative management practices. The level 3 assessment is more quantitative in nature, and is designed to both quantify the distribution and leaching rates of the pesticide with both depth and time, and to validate the risk of contamination identified in the level 1 or level 2 assessments. These three assessment levels are discussed in detail below and summarized in Figure 2.

Level 1: Regional Scale

Regulatory personnel are often required to provide the public with an overview of the potential for groundwater contamination from a specific pesticide being applied to a particular crop within a large agricultural region (e.g., atrazine applied to corn in southwestern Ontario). Because this audience typically has a non–technical background, the evaluation is constrained in that both the assessment methodology and the presentation of the results must be relatively simple. A common approach to implementing such an evaluation involves linking a simple pesticide screening model to a geographical information system, with the assessment results reported in a qualitative manner, such as a relative likelihood ranking, and depicted on a map.

Displaying the relative rankings of individual soil polygons as mapped in the field and described in soil survey reports on a regional scale is not feasible because the detailed scale of the field measurements can not be displayed on the final map. For example, soil polygons may be defined at a scale of 1:25,000 whereas the scale of the final assessment map may be 1:5,000,000. Therefore, a larger area or district is defined and the values for a particular soil property of all the soil series and soil polygons throughout this district are assigned a single averaged or representative regional value, which is then used to produce a single assessment ranking for this district. Unfortunately, the problem with using a single weighted contamination potential over an entire heterogeneous system, is that the severity of the districts that are very likely to be contaminated will appear to be reduced, and the severity of the less susceptible districts will appear to be increased. For example, if half the soils of a district are ranked as an extremely high risk, and the other half of the district is ranked as absolutely no risk, then the weighted averaged ranking for the district would be marginal risk. Hence, the assessment is typically meaningless.

The level 1 assessment methodology proposed here still produces an overall assessment for a large area. However, rather than calculating a single number to rank the potential for groundwater contamination, the level 1 assessment produces a probability distribution of the degree of likelihood for contamination of all soils for each district within the region (Figure 3). A user can quickly and easily compare the proportion of the soils in each district on which a particular crop is grown to the relative potential for groundwater contamination, and hence which districts are most susceptible to groundwater contamination. The soils are also listed according to their relative susceptibility to contamination (Figure 4). However, because of the scale of investigation, the exact location of the high or low risk soils are not mapped.

Because a level 1 assessment only requires a basic assessment of the potential for groundwater contamination, we have selected the AF screening model (Rao et al. 1985) for this task. Although several screening models exist which could be used for this assessment, the AF screening model has been selected because, first, it incorporates the principal soil, site, and pesticide characteristics that control the mobility and persistence of a pesticide in the subsurface, and second, the parameters required by this model are commonly obtained from the literature or soil survey studies.

The AF model does not simulate the migration of a pesticide to the water table, and hence can not quantify pesticide distribution or leaching rates within the soil profile. Rather, this model is designed to calculate the fractional amount of pesticide applied at the ground surface that will infiltrate through a soil profile to the water table. This value can then be used to rank the potential for a pesticide to leach to the water table through a soil profile with respect to other soil profiles or pesticides. The AF model is a function of soil characteristics, pesticide properties, depth to the water table, and infiltration rates related to the principal processes controlling the mobility and persistence of the pesticide in the subsurface, such as advective transport, adsorption, volatilization and first–order degradation:

$$AF = \exp\left(\frac{-0.69 \cdot d \cdot RF \cdot \theta_{FC}}{q \cdot t_{1/2}}\right) \tag{1}$$

where AF is the attenuation factor index representing the fractional amount of pesticide reaching the water table for the soil profile, d is the distance to the water table, θ_{FC} is the soil–water content at field capacity, q is the net annual groundwater recharge, $t_{1/2}$ is the half–life of the pesticide in soil, and RF is a retardation factor index defined as:

$$RF = 1 + \frac{\rho_b \cdot f_{oc} \cdot K_{oc}}{\theta_{FC}} + \frac{n_a \cdot H}{\theta_{FC}} \quad (2)$$

where ρ_b is the bulk density of the soil, f_{oc} is the fraction of organic carbon, K_{oc} is the organic carbon partition coefficient, n_a is the soil air–filled porosity, and H is the dimensionless Henry's Law coefficient.

Although the AF model was designed for a homogeneous soil profile, the model has been modified to account for the layering in natural soil profiles. The AF and RF values for a soil profile are calculated as individual values for each soil layer or horizon with the parameter d in equation (1) representing the thickness of an individual layer. The individual AF and RF values are combined to provide a representative value for the entire soil profile:

$$AF = \Pi AF_i \quad (3)$$

$$RF = \sum RF_i \cdot d_i \quad (4)$$

It is often difficult to undertake a meaningful comparison among several soils of the potential for a pesticide to contaminate groundwater because the depth of the water table varies both temporally and spatially and is seldom reported in soil survey literature. In order to evaluate only the effects of the soil properties and to maintain consistency among soil profiles, a compliance depth is used rather than the depth to the water table. A compliance depth is defined here as a consistent depth at which the pesticide leaching is evaluated for regulatory purposes.

The values of the AF and RF indices are interpreted on a relative basis. The RF index gives a relative indication of the likelihood for a pesticide to be retained in a given soil, whereas the AF index represents the fraction of pesticide applied at ground surface that will leach to the water table at a particular site before it degrades. When comparing several soil profiles, the soil profile with the larger AF index has a greater likelihood of having soil characteristics which would allow a pesticide to leach to the water table than a soil profile with a smaller AF index. A larger value of the RF index indicates that the pesticide is more likely to be retained in the soil profile (i.e., removed from the dissolved phase through adsorption or volatilization) than a soil with a smaller RF index. Because the AF value represents a fractional amount of pesticide reaching the water table, an arbitrary scale, used by Loague (1991) and Loague et al. (1990), can be used to classify the likelihood for groundwater contamination within a decision making framework (Table 1).

Most tasks involved in undertaking a level 1 assessment are, in keeping with the objective of developing an assessment methodology that is easy to use, handled by the computer software. To undertake a level 1 assessment, the user selects the crop of interest within the region from a list. This will in turn display a list of pesticides that are applied to that crop. Once the crop and the pesticide have been selected, all soils in each district in which the crop is grown will be identified, and the values of the pertinent soil characteristics and pesticide properties required by the AF model to undertake the assessment will be retrieved from the database. For each district in the region, the relative ranking of the likelihood for groundwater contamination when the pesticide is applied to the soils is categorized according to the AF contamination potential scale (Table 1) and by the proportion of the total area of the soils on which crop is grown (Figure 3). The probability distributions, based on the AF likelihood rankings from all of the districts are combined and displayed on a single map through RAISON (Figure 4). This involved the use of the graphics module where the bar graphs were created then, along with the legend, overlaid onto the map.

Table 1. Scale for ranking the likelihood for groundwater contamination with the AF model (from Loague et al., 1990).

AF indices	Likelihood
$2.5 \times 10^{-1} < AF \leq 1.0$	very likely
$1.0 \times 10^{-1} < AF \leq 2.5 \times 10^{-1}$	likely
$1.0 \times 10^{-2} < AF \leq 1.0 \times 10^{-1}$	moderately likely
$1.0 \times 10^{-4} < AF \leq 1.0 \times 10^{-2}$	unlikely
$0.0 \leq AF \leq 1.0 \times 10^{-4}$	very unlikely

Level 2: Local Scale

Although a relative assessment for the potential for groundwater contamination for a large region undertaken through a level 1 assessment is useful for providing a general overview of the potential for groundwater contamination within a large region, it does not locate the areas of risk. A level 2 assessment is designed to undertake a relative ranking of the likelihood for groundwater contamination for every soil series within the district, and to display the potential for groundwater contamination according to the actual mapped distribution of the soils or soil polygons (Figure 5). In Figure 5, the the area near Port Stanley on the coast of Lake Erie (see Figure 1) has been enlarged to clearly illustrate the individual soil polygons. The level 2 assessment is useful for indicating which soils have the potential groundwater contamination problem and identifying more precisely the localities where these problem areas exist within the defined district. A level 2 assessment focuses on a smaller scale of investigation, and specifically, examines one of the individual districts defined at the level 1 scale.

A level 2 assessment is required to both undertake the assessment quickly and to report the results of the assessment in a qualitative manner (i.e., relative likelihood ranking). Therefore, the level 2 assessment again uses the AF screening model (Rao et al. 1985) used by the level 1 assessment. However, rather than producing a probability distribution of the likelihood for groundwater contamination representing all soils within the district, the results of the level 2 assessment assigns a likelihood ranking to each soil polygon in the district. Figure 6 shows the likelihood ranking assigned to each individual soil polygon of in the enlargement of Figure 5.

To undertake a level 2 assessment, the user first selects the district, crop, and pesticide of interest within the region from lists provided by the system. Once selected, all soils in that district on which the crop is grown will be identified. Their spatial distributions, values of the pertinent soil characteristics, and pesticide properties required by the AF model to undertake the assessment will be retrieved from the database. The spatial distribution of soils within the district can be displayed (Figure 5). The relative ranking of the likelihood for groundwater contamination when the pesticide is applied to the soils is categorized according to the AF contamination potential scale (Table 1). This scale was supplied to the RAISON system as an ACSII file and was used to categorize each soil polygon using the soil data. The polygons were then coloured using the RAISON thermic mapping function as shown by Figure 6.

Level 3: Soil Profile Scale

A level 3 assessment is designed to quantitatively evaluate the fate of a pesticide within a specific soil profile. This involves simulating the migration of a pesticide through the soil profile to the water table, and quantifying the distribution of the pesticide into its dissolved, sorbed and volatilized components, with respect to time and depth. This assessment focuses on one specific soil profile and one pesticide.

There are two primary reasons for undertaking a level 3 assessment. First, the assessment can be used to identify the processes or factors that have the greatest impact on the leaching of the pesticide identified in level 2, and to evaluate potential means to reduce the pesticide flux to the water table. Second, a level 3 assessment can be used to check the ranking results obtained from a level 1 or 2 assessment.

The two models incorporated into the system that simulate the processes involved in the transport and fate of a pesticide in the soil profile are PRZM (Carsel et al. 1984) and LEACHM (Wagenet and Hutson 1987). Both of these models allow the user to quantitatively predict the concentration, distribution and migration rates of a pesticide and its degradation products within the subsurface with respect to both time and depth. The two models differ from each other in the level of detail that is incorporated into the description of the process involved, the amount and type of data required to undertake a simulation, and the execution time for a simulation. LEACHM is a research model that attempts to describe the processes involved in full mathematical detail, while PRZM invokes a simplified lumped parameter model that reduces both the amount of input data and the time required to obtain results. LEACHM is also able to simulate the fate of the metabolites that may be generated during the degradation of the parent species, while PRZM is restricted to a single pesticide species.

The procedure for undertaking a simulation (level 3 assessment) is more complex than the procedure for undertaking a level 1 or level 2 assessment. However, in keeping with the objective of making this system easy to use, the simulation models are accessed through the EXPRES expert system (Crowe and Mutch, 1991, 1994). EXPRES guides the user through all the steps required to select the simulation model best suited for the objectives of the study, select the appropriate site, pesticide, and crop data in order to construct an input data set, select the output best suited to the assessment objects, perform integrity checks on user supplied information, execute the model and aid in the assessment of the simulation results. The basic steps involved in undertaking a level 3 assessment are as follows. The user enters the objectives of the assessment, and EXPRES selects the appropriate simulation model. The user then either selects a pesticide and agricultural region of interest from lists of those contained in the database as well as the type of output required for the assessment. All pertinent information required to construct an input data set for the simulation models are retrieved and the appropriate input data set is constructed. Alternatively, the user may either select an appropriate pesticide and/or agricultural region from the database, and then modify any of the values of these default data for a pesticide, site, crop, agricultural practice, soil profile, and meteorological conditions to construct a new or modified agricultural setting. EXPRES then subjects all user–supplied information and data to a series of checks to ensure that the data are complete, consistent and meaningful. Once the input data set is complete, EXPRES performs the simulation, and organizes and displays the simulation results in a form that will allow the user to easily obtain the desired information for their assessment in a quick and efficient manner. These output include approximately 50 different types of information, including plots of the distribution of a pesticide and/or degradation products with depth at specific times, or time series plots of pesticide concentration or flux at specific depths (Figure 7). A detailed discussion of the procedure for undertaking a simulation is presented in Mutch et al. (1993).

Data Requirements

As noted above, each of the three assessment levels requires different amounts and different types of data in order to undertake an assessment. All three assessment levels require information on the environmental properties of pesticides including organic–carbon partition coefficient, vapour pressure or Henry's Law constant, half–life in soil, etc., physical characteristics of the soil profile including thickness of each horizon, organic carbon content, field capacity, porosity, etc., and hydrological characteristics of the site including depth to the water table or a compliance depth, rainfall or infiltration rate. Additional data are required for the more complex simulation models such as pesticide application rates, and crop planting, growing and harvesting schedules.

Most of the data required by the screening and simulation models are readily available. The soil characteristics are commonly reported in soil survey reports, as well as the area occupied by the soils and their spatial distribution. Several of the existing databases of the chemical properties of pesticides have been reviewed, such as Worthing and Hance (1991), Howard et al. (1991) and Wauchope et al. (1992), and a set of recommended values for over 170 pesticides were compiled. Meteorological data, such as daily temperature, precipitation, and evaporation, were obtained from Environment Canada's Atmospheric Environment Service. Farm management practices, crop schedules, and pesticide used were obtained through personal communications with staff at the regional Agriculture Canada field stations. These databases are designed to be easily updated and expanded by the user.

Unfortunately, not all of the values of the soil properties required by the model are available in the soils survey reports. This is especially the case for the older soils survey reports, which typically list only the soil series, thickness of horizons, and a qualitative description of the soil texture. In many cases, values required by the models are not directly available from the soil reports. However, sufficient alternative information can be used to estimate the missing values using valid estimation techniques. This will increase the number of soil profiles that can be assessed, and hence enable the user to undertake a more comprehensive and detailed assessment.

Table 2. An example of the estimation levels and techniques used to calculate soil properties for the field capacity (θ_{FC}) of the soil.

Level 1	• given:	% moisture retention of the soil at 33 kPa (-1/3 bar)
	• use:	convert given value to a decimal equivalent (e.g., *13.5 kPa = a field capacity of 0.135*)
Level 2	• given:	% sand, % clay, % organic matter, bulk density of the soil
	• use:	θ_{FC} = 0.4180 - (0.0021•%sd) + (0.035•%cl) + (0.0232•%om) - (0.0859•BD)
Level 3	• given:	% sand, % clay, graph from Carsel et al. (1984)
	• use:	obtain a value from a graph of % sand vs. % clay vs field capacity
Level 4	• given:	a qualitative description of the soil texture
	• use:	table of soil texture vs. field capacity values (e.g., *if the soil texture is a very fine sandy loam, then* θ_{FC} *= 0.225*)

The application of the estimation techniques is handled internally by the system by having the user simply choose to include the soil profiles for which the missing values can be estimated. The estimation procedure proceeds through four stages, with a higher estimation level corresponding to a technique that produces a less precise estimated value. An example of these four levels for estimating the field capacity of a soil is given in Table 2. The first estimation stage uses an analytical expression that represents an exact relationship between the required parameter and the available information. The second stage also uses analytical expressions, but the relationship between the required parameter and available data is not exact, but is an approximation relationship. The third estimate stage uses qualitative or semi–qualitative methods to estimate a value for a parameter. The semi–qualitative method makes use of given values of the % sand and % clay of the soil, plotted on a graph onto which values of the desired parameter are contoured. The fourth estimation stage makes use of the statistical analysis of soil properties from over 250 soils in southwestern Ontario. This method uses a table of qualitative descriptions of soil texture, such as a sandy loam or a silty clay, to find a corresponding typical value for that descriptive term.

APPLICATION OF THE ASSESSMENT SYSTEM

The multi–level assessment approach was applied to six counties (Brant, Elgin, Haldimand–Norfolk, Middlesex, Niagara and Oxford) of southwestern Ontario, Canada (Figure 1). Corn and tobacco are major crops grown in this region, and pesticides commonly used here include atrazine, metolachlor, alachlor, metribuzin and cyanazine.

The results of the following assessments were compared to a recent study conducted to ascertain the extent of agricultural contaminants in rural wells (WCGR 1992). Included in this study were the pesticides atrazine, metolachlor, metribuzin, alachlor, and cyanazine. Although this study focused on contamination of wells, information was compiled from this study to evaluate the extent of contamination of the shallow groundwater from pesticides. Atrazine was by far the most common pesticide detected in the groundwater samples from shallow wells (< 10 m deep), with 47 detections of atrazine, 6 detections of metolachlor, 0 detections of the other three pesticides, out of 182 groundwater samples (Table 3). The concentrations of atrazine and metolachlor were almost always below drinking water guidelines.

Table 3. Pesticides in detected in shallow (< 10 m) wells in southwestern Ontario. (data compiled from WCGR 1992).

County	Winter 1992		Summer 1992	
	wells sampled	pesticides detected*	wells sampled	pesticides detected*
Brant	2	1xA	2	2xA
Elgin	21	6xA, 1xA,M	19	7xA, 2xA,M
Haldimand-Norfolk	31	2xA	30	4xA
Middlesex	22	5xA, 1xA,M	22	7xA, 1xA,M
Niagara	4	1xA	3	2xA
Oxford	13	2xA, 1xA,M	13	2xA

* 6xA - indicated only atrazine detected in 6 samples
1xA,M - indicates both atrazine and metolachlor detected in 1 sample

The level one assessment provides a quick visual comparison on a county by county basis of the relative potential for a pesticide to leach to the water table in the corn growing areas of the counties. Hence, the objective is to determine which region is most susceptible to contamination. Three pesticides, atrazine, cyanazine and metolachlor, were assessed here. The results of the assessment indicate that atrazine is more likely to leach to the water table in all six counties (Figure 3) than metolachlor (Figure 8). The ranking for cyanazine (not shown) is 100% very unlikely to leach in all six counties. These results were verified by the above noted study (WCGR 1992). When assessing the overall relative susceptibility of various regions to contamination, the advantage of incorporating the area of the county occupied by a soil into the assessment is evident in the level one assessment. Although 31.3% of the soils in Elgin county on which corn is grown are categorized as being unlikely to cause groundwater contamination from atrazine, these soils occupy only 7.2% of the area of the corn growing region of Elgin county (Table 4). Similarly, although 15.6% of these soils are categorized as being very unlikely to cause groundwater contamination from metolachlor, these soils only occupy less than 2% of Elgin county (Table 4). Overall, the soils of Elgin, Brant and Haldimand-Norfolk counties were predicted to be most susceptible to contamination from atrazine and metolachlor. The counties least susceptible to groundwater contamination from both atrazine and metolachlor are Niagara and Oxford. Although the level one assessment does list the soils and their areas within each likelihood category (Figure 4), a level two assessment is required to locate the areas within a county that are susceptible to contamination.

Table 4. Area of Elgin county susceptible to groundwater contamination compared to proportion of soils susceptible to groundwater contamination.

susceptibility category	atrazine		metolachlor	
	% soils	% area	% soils	% area
very likely	0.0	0.0	0.0	0.0
likely	9.4	17.7	0.0	0.0
moderately likely	59.4	75.0	15.6	24.3
unlikely	31.3	7.2	68.8	74.0
very unlikely	0.0	0.0	15.6	1.7

The objective in undertaking a level two assessment is to show the areas that are most susceptible to groundwater contamination. Elgin County is selected because it has the highest potential for groundwater contamination from the application of atrazine as compared to the other counties and Elgin County also exhibited the greatest number of detections of pesticides with a level one assessment. A total of 64 soils (Figure 5) were categorized and mapped according to their likelihood for groundwater contamination from atrazine and metolachlor. Figure 6 is an example of this map and represents the enlarged are shown in Figure 5. The incidence of atrazine and metolachlor detected in the groundwater samples obtained during the WCGR (1992) sampling program are listed in Table 5 along with the soil at the sampling location. Also listed on Table 5 are the results of the model predictions summarized to rank and categorize only those soils from which groundwater samples were collected. The model predicted that the Fox, Plainfield, and Waterin soils were most susceptible to groundwater contamination. In general, the soils with the higher ranking showed a higher incidence of pesticide contamination (Table 5). The model also predicted that the soils were most susceptible to contamination from atrazine and less susceptible to contamination from metolachor (Table 5). These predictions are reflected by the incidences of atrazine and metolachlor detected.

Table 5. Comparison of pesticides detections in shallow (< 10 m) wells to soils in Elgin County. (data compiled from WCGR 1992).

Soil	wells sampled	atrazine detected[1]	rank[2]	leaching potential[3]	metolachlor detected[1]	rank[2]	leaching potential[3]
Fox	10	-	1	(L)	-	1	(M)
Plainfield	4	2xA	2	(L)	-	3	(M)
Waterin	2	2xA	7	(L)	-	8	(M)
Muriel	12	6xA	14	(M)	2xM	14	(U)
Berrien	6	6xA	19	(M)	1xM	22	(U)
Gobles	4	-	22	(U)	-	24	(U)
Haldimand	2	-	53	(U)	-	50	(U)

1 6xA - indicates atrazine detected in 6 samples; 1xM - indicates metolachlor detected in 1 sample
2 rank out of 64 soils
3 leaching potential: (L)=Likely, (M)=Moderately Likely, (U)=Unlikely

Although the results of the previous assessments indicated that the Fox soil of Elgin County is most susceptible to contamination, field data indicated that the incidence of pesticide detected in groundwater samples from the Berrien and Muriel soils was greater that in the Fox soils (Table 5). A level 3 assessment, specifically focuses on simulating the migration and fate of pesticides in these soils, is used to verify the results of the levels one and two assessments. Pedological characteristics of representative soil profiles of the Fox, Muriel, and Berrien soils, used as input data for the simulations, are listed in Table 6.

Table 6. Detailed soil profile characteristics and analyses of the Fox, Muriel, and Berrien soils of Elgin County (from Schut 1992).

Soil: Fox

horz.	depth cm	texture	%sd	%si	%cl	%om	den. gm/cm^3	por.	Ks cm/hr	%moisture retent. 33kPa	1500kPa
Ap1	23	S	89	7	4	1.3	1.56	.40	7.2	6.3	3.9
Ap2	29	S	88	8	4	0.8	1.55	.41	~8.0	6.2	3.7
Bm	53	S	92	6	2	0.1	1.50	.44	10.3	4.8	3.0
Bt1	65	S	88	7	5	0.1	1.51	.46	11.6	3.9	3.1
Bt2	68	LS	87	6	6	0.2	1.55	.39	~10.0	7.4	3.9
Ck	-	S	95	4	1	0.1	1.51	.44	14.4	2.6	1.2

Soil: Berrien

horz.	depth cm	texture	%sd	%si	%cl	%om	den. gm/cm^3	por.	Ks cm/hr	%moisture retent. 33kPa	1500kPa
Ap	26	FSL	74	15	10	4.8	1.27	.48	1.33	19.3	6.9
Bmgjt	45	LFS	83	6	11	0.4	1.43	.45	2.34	7.4	2.4
Ckgj	60	FS	88	7	5	~0.1	1.45	.48	1.94	3.6	1.3
IICkgj	-	SIC	2	54	44	~0.1	1.44	.45	0.04	19.9	13.4

Soil: Muriel

horz.	depth cm	texture	%sd	%si	%cl	%om	den. gm/cm^3	por.	Ks cm/hr	%moisture retent. 33kPa	1500kPa
Ap	21	CL	24	41	35	2.3	1.44	.44	1.27	21.5	18.4
Bmgj	29	CL	22	40	38	1.9	1.43	.45	0.76	19.9	15.5
Btgj	47	C	17	39	43	0.7	1.38	.47	<0.15	20.1	16.3
Ckgj	-	SICL	20	45	35	~0.1	1.55	.41	<0.15	17.8	13.9

The simulation of the fate of atrazine does verify the results of the level one and level two assessments, in that groundwater beneath the Fox soil is more susceptible to contamination than the Berrien and Muriel soils. The time series plot of the concentration of dissolved atrazine at the water table shows that the peak concentration of atrazine leaches to the water table through the Fox soil faster that through the Berrien and Muriel soils (Figure 7) and its peak concentration is higher for the Fox soil than the Berrien and Muriel soils.

Even when accounting for uncertainty and variability of the soil parameters, the Berrien and Muriel soils are more susceptible to contamination than the Fox soil. Two parameters that strongly influence the migration rate and retention of the pesticide, saturated hydraulic conductivity and organic carbon content of the two soils, were varied within a range typical of natural conditions, and leaching of the pesticide was simulated. When the organic carbon content of the Berrien and

Muriel soils were decreased by 50%, the maximum concentrations of dissolved atrazine at the water table were still considerably less then that for the Fox soil (Table 7). Similarly, when the saturated hydraulic conductivity of the Berrien and Muriel soils were increase by one order of magnitude, the maximum concentration of dissolved atrazine at the water table was still much less than that calculated for the Fox soil. Also, in both cases the time for atrazine to reach the water table was still much longer for the Berrien and Muriel soils than for the Fox soil (Table 7)

Table 7. Summary of simulations of atrazine transport through the Fox, Muriel and Berrien Soils.

Soil	Sensitivity Analysis Parameter[1] % o.c.	K_{sat}	max. conc. at w.t. (mg/L)	time to reach w.t. (days)
Fox	--	--	1.60×10^{-2}	816
Berrien	--	--	1.57×10^{-3}	942
Berrien	x 0.5	--	2.08×10^{-3}	863
Berrien	--	x 10	2.92×10^{-3}	880
Muriel	--	--	5.11×10^{-3}	857
Muriel	x 0.5	--	5.70×10^{-3}	859
Muriel	--	x 10	5.92×10^{-3}	880

1 % o.c. - percent organic carbon content of the soil
K_{sat} - saturated hydraulic conductivity of the soil

SUMMARY

Assessing the potential for groundwater contamination from pesticide usage, or predicting the fate of a pesticide in the subsurface requires an extensive and complex set of field and laboratory data, numerical models and expertise. Further, for non–experts in this field to undertake this task requires an environmental information system that combines the assessment models and databases, with GIS, spreadsheets, and graphical packages, within an expert system framework that permits the non–expert to easily undertake an accurate and meaningful assessment.

A multi–level pesticide assessment methodology has been developed here that will permit regulatory personnel to undertake a variety of assessments on the potential for pesticide usage in agricultural areas to contaminate the groundwater regime. A multi–level approach accounts for a variety of assessment objectives, varying detail required in the assessment, the restrictions on the availability and accuracy of data, the time available to undertake the assessment, and the expertise of the decision maker. The three assessment levels correspond to more precise and reliable assessments, the use of more comprehensive assessment methodologies and models, and substantially more detailed data.

The Level 1 or regional scale is designed to assess and rank the likelihood for groundwater contamination from a specific pesticide applied to a particular crop throughout an agricultural

region. The Level 2 or local scale assesses the likelihood to which all soils within a county on which a particular crop is grown will allow groundwater contamination from a specific pesticide. A Level 3 or soil profile scale allows the user to simulate the migration of a pesticide within a soil profile, and hence quantify the distribution and leaching rates of the pesticide with both depth and time.

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FIGURES

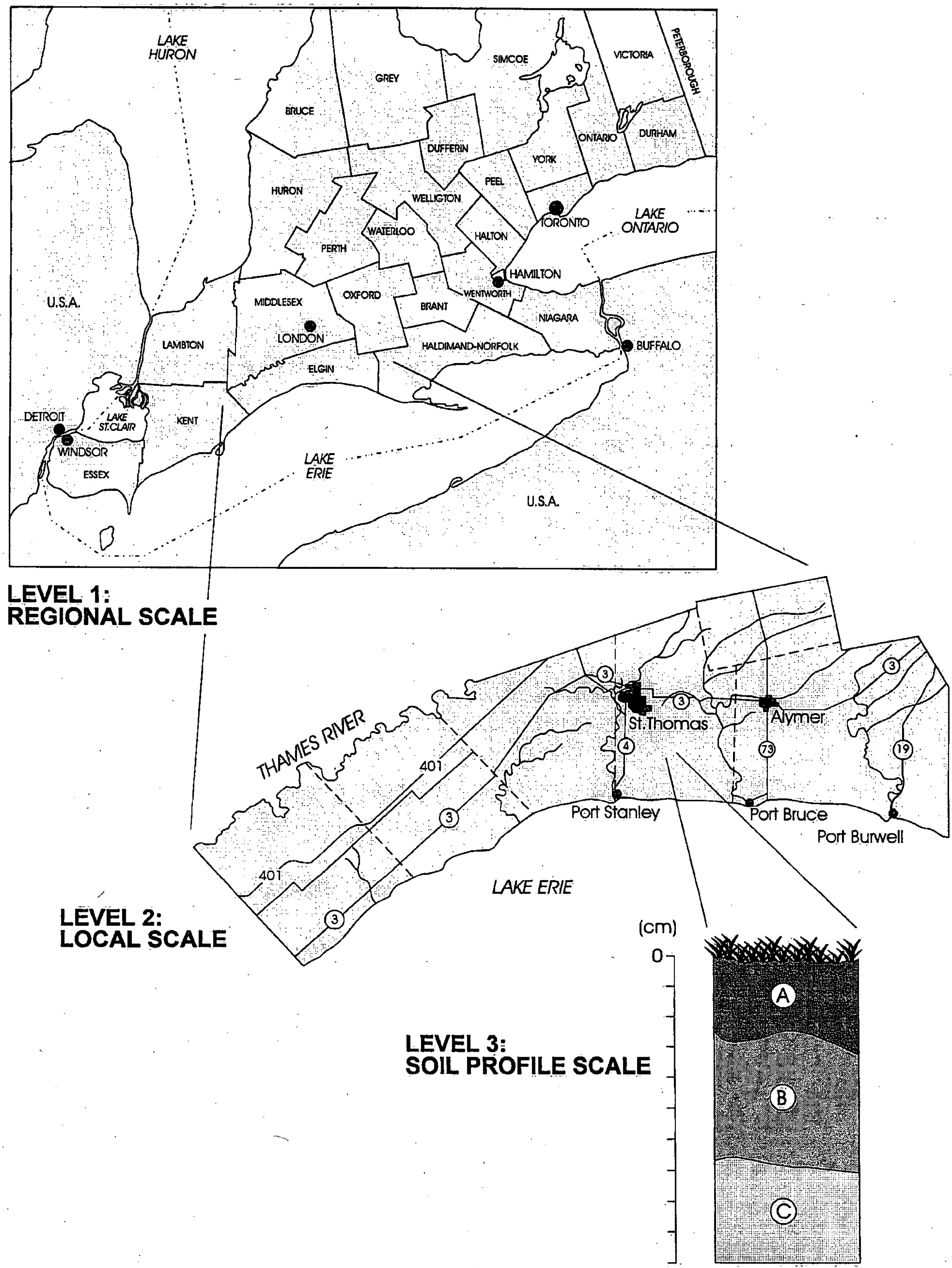

Figure 1. Geographical scales evaluated with the multilevel approach to the assessment of the potential for groundwater contamination from pesticides

User's Selection	System Result
Level 1:	
· select crop	· search for counties growing that crop · identify soils growing that crop · retrieve soil data · estimate missing values
· select pesticide	· retrieve pesticide values
· continue	· undertake the assessment
Level 2:	
· select county	· search and display crop grown
· select crop	· search and display all soils growing that crop · retrieve soil data · estimate missing values
· select pesticide	· retrieve pesticide data · estimate missing values
· continue	· undertake the assessment
Level 3:	
· select simulation objectives	· select simulation model
· select agricultural region	· retrieve soil, crop meteorological data
· select pesticide	· retrieve pesticide data
· modify pesticide, crop, soil, etc., data	· modify input data set
· select required output	· modify input data set
· continue	· run the simulation

Figure 2. Summary of the user's steps and the assessment system's responses involved in the three levels of the pesticide assessment procedure.

F1:Next-Scrn F2:Previous Scrn F5:Exit F6:Notes F7:Help F8:Instructions

EXPRES

POTENTIAL SUSCEPTIBILITY TO CONTAMINATION

County: Elgin
Crop: Corn
Pesticide: Atrazine

Likelihood	# of Soils	% Area
Very Likely	0	0.0
Likely	2	8.0
Moderately Likely	38	82.6
Unlikely	22	9.2
Very Unlikely	2	0.2

Soils	Area
Fox	949 ha
Plainfield	11561 ha

Figure 3. Comparison among several counties of the percentage of soils within each likelihood class for the potential for groundwater contamination from atrazine.

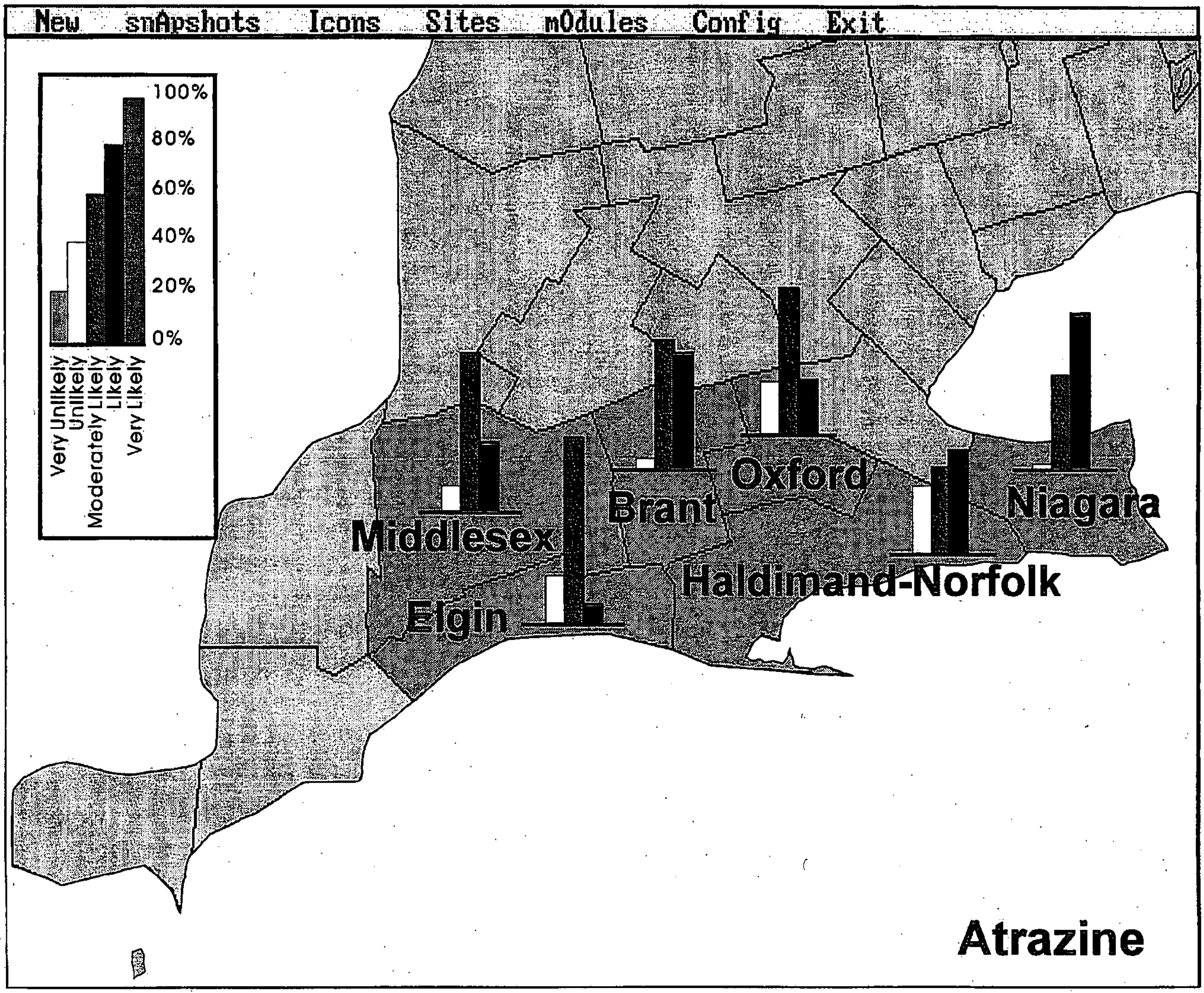

Figure 4. Ranking of the susceptibility of the soils to groundwater contamination from atrazine.

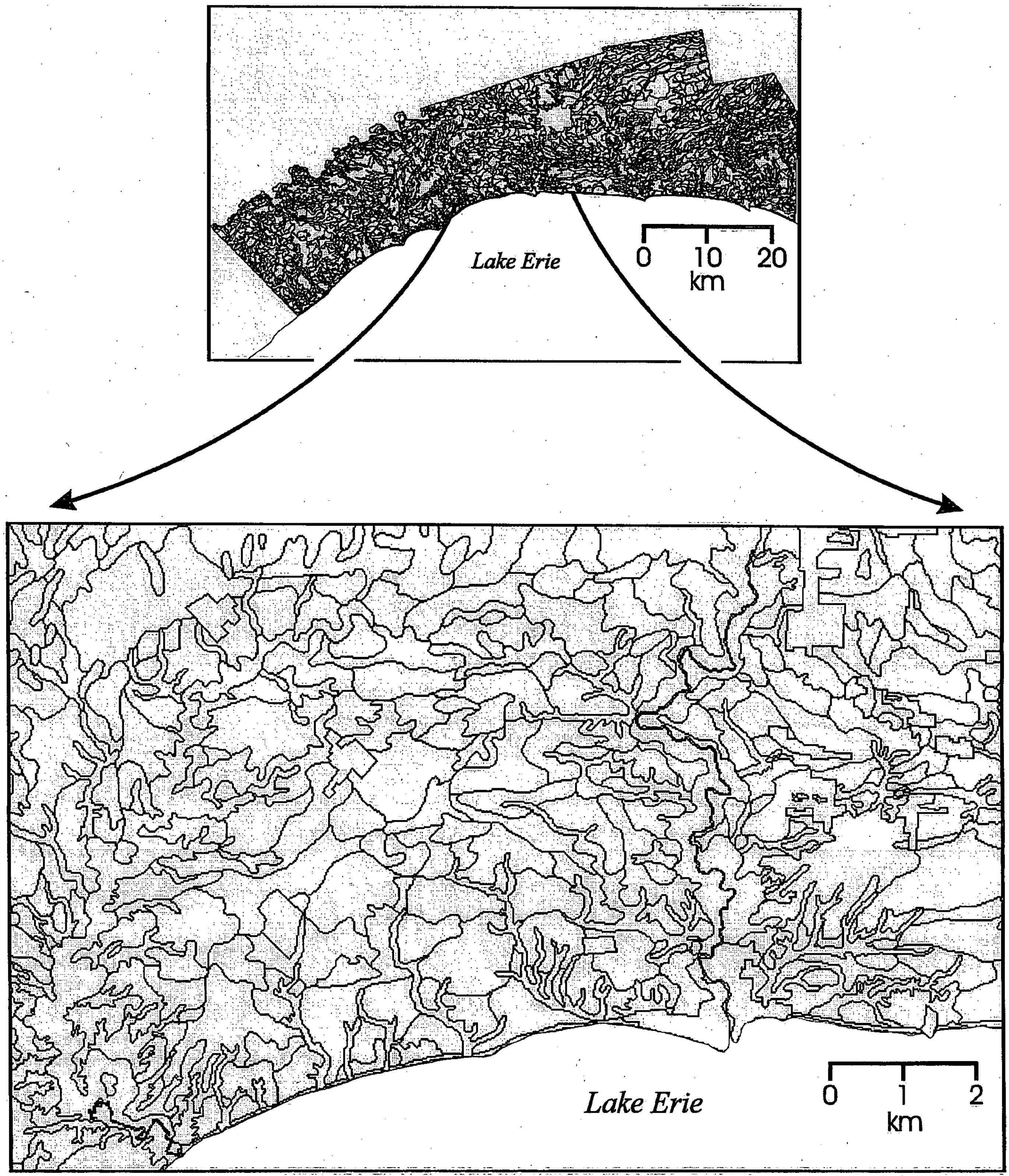

Figure 5. Distribution of soil types mapped in Elgin County, including an enlarged area near Port Stanley.

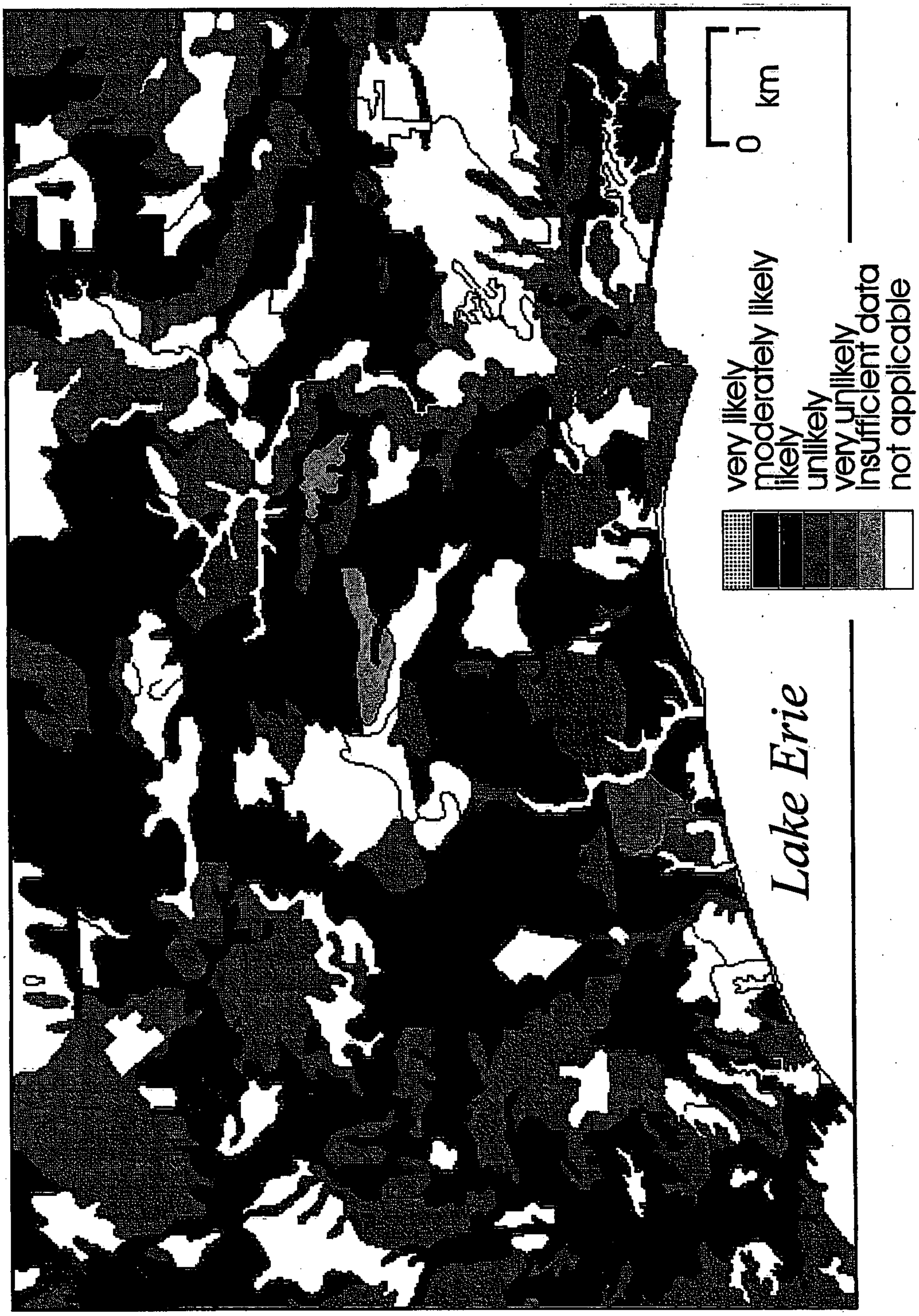

Figure 6. The likelihood ranking of the potential for groundwater contamination from atrazine assigned to each soil polygon of the portion of Elgin County enlarged in Figure 5.

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