GUIDE TO GROUNDWATER SENSITIVITY RATING TECHNIQUES

by
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INTRODUCTION

The protection of ground water quality has become an important issue in recent years. Ground water systems have traditionally been viewed as inexhaustible sources of clean water, but it is now clear that they require sound management and protection if they are to continue to provide the needs of modern society. Land use practices such as agriculture, waste disposal and underground storage can cause extensive ground water pollution problems if improperly managed. On the other hand, proper planning and management can minimize adverse environmental impacts.

Various scientific techniques have been developed to help understand and manage ground water. A broad array of technical methodologies exists ranging from simple indices to sophisticated mathematical techniques, each with particular applications. Mathematical techniques include flow models and solute transport models (Canter and Knox, 1985a). These have good predictive capabilities but are usually data-intensive, time-consuming and expensive to use. Their application usually requires considerable scientific and technical expertise. Consequently, complex hydrologic models are well-suited for intensive contaminant studies and long-term scientific research, but are not well-suited to preliminary studies where data is scarce (LeGrand, 1983). The complexity of these models also can render them inappropriate for the time and budgetary constraints of local or regional planning agencies. Water managers at this level often lack the resources and expertise to implement high-powered mathematical models.

This document reviews a set of simple techniques designed for use at the local level known as empirical assessment methodologies; or more simply, "ground water sensitivity indices." These indices are relatively inexpensive, easy to use, and require data that can usually be obtained from existing sources. The disadvantage of indices, however, is that they do not provide quantitative estimates of pollutant transport or loading. They only characterize and rank sites according to relative pollution sensitivity.

Empirical assessment techniques are distinguished from other methodologies by certain characteristic features. They typically assign numerical values to a set of hydrologic factors associated with a particular site. Factor scores are then combined into a final sensitivity score. The sensitivity of several sites can easily be compared because each has been evaluated according to a consistent set of criteria. Canter and Knox (1987) outline five typical features of empirical assessment methodologies:

1. **The explicit development of numerical indices.** Empirical assessment methodologies typically produce a numerical site index that is used to compare relative ground water sensitivity among sites.

2. **Multiple site factor scores.** Site indices are composed of numerically weighted factor scores for a variety of soil, hydrologic, and geologic site characteristics. Weights vary according to their contribution to contamination risk.

3. **A final summation of factor scores.** The site index consists of a summation or product of factor scores giving a relative comparison of ground water vulnerability among sites.

4. **Explicit description of measurement techniques.** Techniques are explicitly described for a) measuring and weighing factors, b) developing factor scores, and c) developing the site index from factor scores.

5. **Professional judgement** is needed to interpret the final scores.

There are two basic approaches to managing ground water quality: either prevent problems before they occur or remedy them later. Prevention is a key strategy. Once ground water problems have occurred, they can be difficult or impossible to remedy. Engineering solutions are usually expensive, while natural processes of flushing and chemical degradation can take decades or even centuries to reduce pollutant concentrations to acceptable levels.

Empirical assessment methods have applications in both prevention and remediation strategies. When used in prevention strategies, for example, several candidate landfill sites can be ranked prior to selection and the most suitable candidate chosen. Similarly, existing waste sites can be compared and ranked for remediation according to pollution potential.

Unfortunately, documentation for these methodologies is extensive and widely scattered. At least 25 techniques are currently in use. Various hybrid methodologies have also been developed by governmental or consulting agencies. Techniques are published in books, journals and government documents which are scattered and often difficult to locate. In addition, existing methodologies are designed for varying purposes and scales. The result is that potential users have to sort through a bewildering and often obscure array of technical material and often are not aware of the spectrum of tools available.

HOW TO USE THIS DOCUMENT

The purpose of this review is to catalogue techniques in a form that is useful for managers who want to select a ground water assessment methodology, but do not have time to hunt through stacks of technical journals. It is organized to help users locate and choose appropriate techniques for their particular needs from six categories of intended use. Within each use category, individual techniques are compared and succinct descriptions of each are provided.

The six use categories are outlined in the *Guidelines* beginning on page three, and correspond to Sections 1 through 6 of this document. Before proceeding to the *Guidelines*, users should consider what information they hope to gain from using ground water assessment techniques and what data and resources are available to them. The users should then select categories from the *Guidelines* according to their particular needs. Tables provided in the *Guidelines* briefly compare applications and characteristics of ground water assessment techniques applicable to each category. This preliminary screening helps users select only those techniques which are appropriate for them.

After selecting techniques from the tables in the *Guidelines*, users should refer to appropriate sections of the document for detailed reviews of the techniques. All of the reviews are presented in a standard format which includes: 1) an overview of the method, 2) scale at which it is used, 3) data requirements, 4) method output, and 5) limitations of the method.

It should be emphasized that this document is *not* intended to be a user's manual for any of the techniques reviewed. It is only intended to give the reader an accurate view of each method's structure, complexity, data requirements, and general usage.

GUIDELINES

SELECTING A GROUND WATER SENSITIVITY RATING TECHNIQUE

Ground water sensitivity rating techniques can be organized into six general categories based on intended use. These are techniques to:

1. Select candidate waste disposal sites.
2. Rank existing sites for remediation.
3. Evaluate sensitivity over large areas.
4. Evaluate individual contaminants according to pollution potential.
5. Evaluate candidate sites for land surface treatment.
6. Evaluate pollution potential from oil and gas field activities.

Tables 1 through 6 on the following pages correspond to the six categories outlined above. Each table is an easy-to-use reference for contrast and comparison of methodologies within each category. The tables direct users to Sections 1 through 6 for more detailed reviews of each methodology. Several things must be kept in mind when using the tables:

1. Tables and use categories are meant *only* as general guidelines to help users identify techniques that may be applicable to their needs. They do not represent the final word on how methodologies should be used. They are designed to provide general guidelines rather than fixed rules of application.
2. Tables and use categories tend to be conservative regarding uses and applications. They attempt to reflect explicit intended use as presented in the literature, even though many of the methodologies reviewed were quite vague in this regard. This review employs a minimum of speculation in order to accurately represent the method's original intended purpose, even though possible uses and applications may be omitted.
3. Secondary uses of techniques are included in the tables if references to such uses are explicit and documented. For example, the Surface Impoundment Assessment Method (SIA) was designed for industrial waste impoundments (Silka and Swearingen, 1978). The original manual makes no reference to applications involving septic systems. However, Canter and Knox (1985b) applied the SIA successfully to septic systems in Oklahoma. Therefore, septic system applications of the SIA are included in the tables.
4. Uses and applications provided in the following tables are not exhaustive. For example, EPA's DRASTIC could conceivably be used to screen areas suitable for landfill sites. However, such uses are not explicit in the reviewed literature and not included in the tables.

Table 1. Summary of methodologies used to select candidate waste disposal sites. Techniques in this category are typically used to rank candidate waste disposal sites according to pollution potential. Methodologies are divided into three sub-categories and reviewed in detail in *Section 1.*

Empirical Assess-ment Method	Evaluates Geologic Sensitivity	Evaluates Contaminant Properties	Explicitly Evaluates Hazardous Wastes	Screens Potential Indust. Waste Pond Sites	Screens Potential Septic Sys. Sites	Screens Potential Landfill Sites	Rates Land Waste Treatment Sites	General Planning/ Regulatory Application
LeGRAND (1964)	X			X	X		X	X
SURFACE IMPOUND ASSESSMENT (SIA)	X	X	X	X	X		X	X
SOIL/WASTE INTERACTION MATRIX	X	X	X	X	X		X	X
HAZARDOUS WASTE/LAND-FILL SITE RANKING SYSTEM	X	X	X			X	X	X
LeGRAND (1983)	X	X		X	X	X	X	X

Table 2. Summary of methodologies used to rank existing sites for remediation. These methodologies are divided into four sub-categories and reviewed in detail in *Section 2.*

Empirical Assess-ment Method	Evaluates Geologic Sensitivity	Evaluates Contaminant Properties	Explicitly Evaluates Hazardous Wastes	Rates Existing Industrial Waste Ponds	Rates Existing Septic Systems	Rates Existing Landfill Sites	Rates Land Waste Treatment Sites	General Planning/ Regulatory Application
GEOLOGIC RANKING SYSTEM	X					X		
GROUND WATER CONTAMINATION SITE RANKING METHOD	X	X	X	X		X	X	
NEW JERSEY PRIORITY SYSTEM	X	X	X	X		X		
KANSAS RANKING SYSTEM	X	X		X	X	X	X	
SITE RATING METHODOLOGY	X	X	X	X		X		
HAZARD	X	X	X			X		
MICHIGAN SITE ASSESS-MENT SYSTEM (SAS)	X	X	X	X		X		

Table 3. Summary of methodologies used to evaluate sensitivity over large areas. Techniques in this category are designed to evaluate ground water sensitivity over large geographic areas. Methodologies are divided into two sub-categories and reviewed in detail in *Section 3*.

Empirical Assess-ment Method	Evaluates Geologic Sensitivity	Evaluates Contaminant Properties	Explicitly Evaluates Hazardous Wastes	Screens Areas for Industrial Waste Ponds	Screens Areas for Septic Systems	Screens Areas for Landfill Sites	Screens Areas for Land Waste Treatment	General Planning/ Regulatory Application
DRASTIC	X							X
MINNESOTA SENSITIVITY MAP	X							X
WISCONSIN SENSITIVITY MAP	X							X
ILLINOIS GROUND WATER CONTAMINATION POTENTIAL RATING SYSTEM	X					X		X
MINNESOTA SENSITIVITY RATING METHOD	X			X	X	X	X	X
TROJAN-PERRY METHOD	X	X		X	X	X	X	X

Table 4. Summary of methodologies used to evaluate individual contaminants according to pollution potential. Methodologies are divided into two sub-categories and reviewed in detail in *Section 4*.

Empirical Assess-ment Method	Evaluates Geologic Sensitivity	Evaluates Contaminant Properties	Explicitly Evaluates Hazardous Wastes	Rates Industrial Waste Ponds	Rates Septic System Sites	Rates Landfill Sites	Rates Land Waste Treatment Sites	General Planning/ Regulatory Application
LEACHING INDEX		X						X
PESTICIDE INDEX	X	X						X
PESTICIDE RATING SYSTEM	X	X						

Table 5. Summary of methodologies used to evaluate candidate sites for land surface treatment. Techniques in this category evaluate candidate sites for land surface treatment of hazardous wastes. Methodologies are divided into two sub-categories and reviewed in *Section 5*.

Empirical Assess-ment Method	Evaluates Geologic Sensitivity	Evaluates Contaminant Properties	Explicitly Evaluates Hazardous Wastes	Rates Industrial Waste Pond Sites	Rates Septic System Sites	Rates Landfill Sites	Rates Land Surface Application Sites	General Planning/ Regulatory Application
FULLER LAND TREATMENT METHODOLOGY	X						X	
MOBILITY DEGRADATION INDEX	X	X	X				X	

Table 6. Summary of methodologies to evaluate pollution potential from oil and gas field activities. Methodologies are divided into two sub-categories and reviewed in *Section 6*.

Empirical Assess-ment Method	Estimates General Geologic Sensitivity	Evaluates Contaminant Properties	Rates Production/ Abandoned Wells	Rates Disposal Wells	Evaluates Well Condition	General Planning/ Regulatory Application
OIL/GAS WELL METHOD			X		X	
SALT WATER DISPOSAL WELL METHOD				X	X	
BRINE DISPOSAL METHOD	X			X		

SECTION 1: WASTE DISPOSAL SITE SELECTION

Site selection methodologies provide a preliminary evaluation of candidate sites for waste disposal. They are easy-to-use, first round evaluation techniques for preliminary ranking prior to more rigorous evaluations.

The methodologies described in this section are designed for evaluating three broad types of waste disposal sites:

1. Facilities that accommodate degradable wastes only
   a) LeGrand (1964)
   b) Soil-Waste Interaction Matrix

2. Facilities that accommodate both degradable and non-degradable wastes
   a) LeGrand (1983)
   b) Hazardous Waste/Landfill Site Ranking System

3. Industrial surface impoundments
   a) Surface Impoundment Assessment Methodology (SIA)

LeGrand defines degradable wastes as municipal sludge, sewage and other compounds that decompose rapidly via chemical breakdown. Degradable waste facilities include septic systems, cesspools, and municipal waste facilities.[1]

Non-degradable wastes are defined as chloride, nitrate and similar materials that attenuate slowly via dilution. Non-degradable waste facilities include sanitary landfills and waste dumps.

Industrial surface impoundments include pits, ponds, lagoons and other industrial waste facilities. Waste materials can be disposed of by evaporation, held in storage, treated, or allowed to seep slowly into the underlying earth materials for natural attenuation.

The Surface Impoundment Assessment Methodology (SIA), Soil-Waste Interaction Matrix, and LeGrand (1983) are all based on the work of LeGrand (1964). They are designed for sites at or near the ground surface where loose, granular materials overlie water table aquifers. They are not applicable for sites that affect deep or confined aquifers.

All methods except LeGrand (1964) evaluate contaminant behavior and characteristics to some extent. The Hazardous Waste/Landfill Site Ranking System and Soil-Waste Interaction Matrix are the most rigorous while LeGrand (1964) is the least rigorous.

1.1 DEGRADABLE WASTES ONLY

1.1.1 LeGRAND (1964)

GENERAL PURPOSE

The LeGrand method was developed to give preliminary estimates of ground water pollution potential at points of present or potential water use. Particular applications include:

[1]It should be noted that these sources are often a source of nitrate, which the author defines as "non-degradable".

1. Waste disposal site selection

2. Quick appraisal of sites where hydrologic and hydrogeologic data are scarce

3. Evaluating contamination potential of areas where wastes are released in loose granular earth at or near the ground surface

The LeGrand method is applicable to contaminants that attenuate or decrease in potency with time. These include sewage, detergents, viruses and some types of radioactive wastes. Sources to which the method can be applied include septic systems, cesspools, surface impoundments, industrial lagoons and disposal wells. This method is designed for use in the early stages of planning before land use designations have been made. It is most applicable where waste is applied at or slightly below the land surface.

SCALE

This method is designed to be used on individual sites.

METHOD OVERVIEW

The LeGrand methodology requires estimates of five factors: depth to water table, soil sorption capacity, soil permeability, water table gradient and distance to the nearest point of use. Scales provided in the methodology are used to obtain numerical values for each factor as shown in Figure 1. Three sets of scales are provided for use in different situations:

1. Single media sites in which unconsolidated material extends 100 feet or more below the ground surface (typical of coastal-plain or alluvial deposits in semi-arid regions).

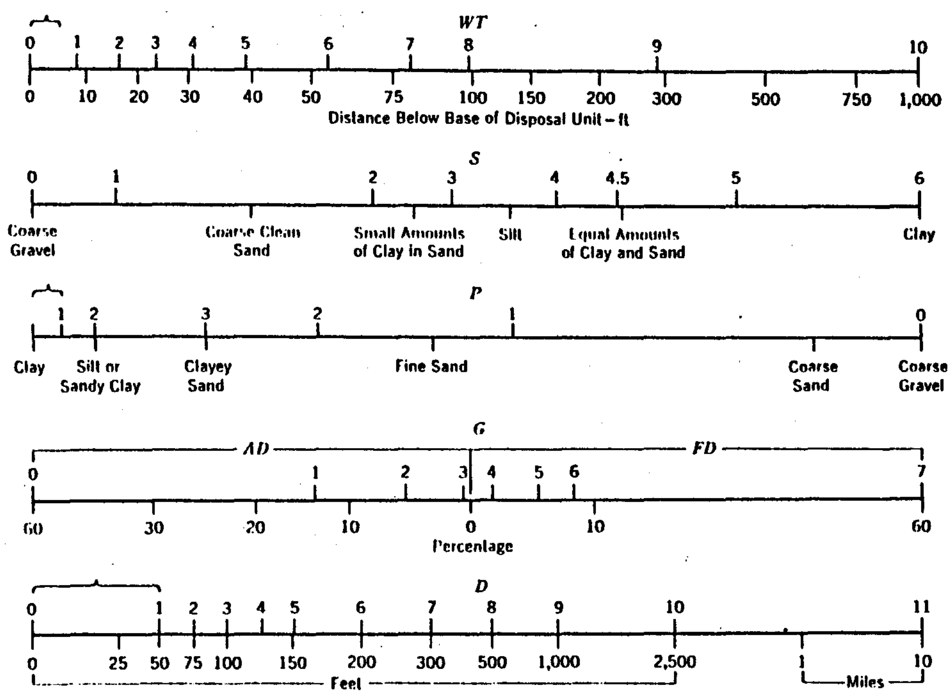


Figure 1. Typical Factor Rating Chart for LeGrand
Source: LeGrand (1964)

2. Two-media sites in which unconsolidated granular materials at the ground surface are underlain at shallow depths by dense rocks (typical of humid regions where either residual soils have developed on consolidated rocks, or glacial or flood plain deposits overlay consolidated rocks).

3. Situations in which radioactive wastes are present.

METHOD OUTPUT

This method produces an index score for a site that can be compared to scores from other sites. The site score is a summation of the five factor scores, and is interpreted as an estimate of the probability that water at the nearest point of use will become contaminated. Low scores (0-8) indicate high probability of contamination, while high scores (25-35) indicate low probability of contamination.

DATA REQUIREMENTS

The LeGrand method is not data intensive, being designed to give quick appraisals of specific sites where the hydrologic and hydrogeologic data are scarce. Five factors are evaluated:

1. **Depth to water table** (feet) -- an average value seasonal high water table. Depth should either be measured directly or taken from existing information such as well logs.

2. **Sorption capacity of soil** -- scales provided in the method are based on qualitative classifications of particle size distribution, i.e., the percentage of gravel, sand, silt and clay present. Soil sampling at the site would give the best estimate, but soil survey or other data can be used.

3. **Soil Permeability** -- classifications in (2) above are also used to estimate permeability.

4. **Water table** --
   a) Flow direction: water flowing toward or away from the point of use
   b) Flow gradient: percent (%) gradient is estimated from a water table map or direct measurements.

5. **Distance to the point of use** (ft) -- e.g., distance to nearest well.

LIMITATIONS OF THE METHOD

1. This system is only useful for one and two media sites as described above. Accuracy of the method is slightly diminished in the latter.

2. This system is only applicable to unconfined aquifers. It is not applicable for deep or artesian aquifers.

3. The system is only useful for evaluating pollution risks involving contaminants that attenuate or decrease in potency through time.

4. This method is not applicable for chemical wastes such as chloride that attenuate only by dilution.

5. The method is not applicable on mixed waste sites such as refuse dumps or sanitary landfills.

6. The method does not take into account vertical differences in permeability, but rather assigns a single average value for a particular site. This can give erroneous estimates because water can travel at faster rates through more permeable layers in a stratified soil profile (i.e., fingering). The implications are that a user

should obtain estimates from the most permeable stratum in the vadose zone. If a high-permeability layer exists in the vadose zone which is not measured, a single estimate could misrepresent actual pollution potential.

Primary source: LeGrand (1964). *Secondary sources:* Canter et al. (1987) and Trojan (1986).

1.1.2 SOIL-WASTE INTERACTION MATRIX

GENERAL PURPOSE

The Soil-Waste Interaction Matrix is used to determine site suitability for disposal of industrial wastes. The procedure developed in this method can be used to accomplish three tasks:

1. Rank chemical wastes according to their properties and environmental behavior.

2. Rank potential disposal sites according to their soil, hydrologic and topographic characteristics. The methodology is based on LeGrand (1964).

3. Evaluate and rank various specific waste-site combinations in order of potential environmental risk.

SCALE

This method is designed to be used on individual sites. However, it has been used in subdivisions containing several hundred individual septic tank systems (Canter and Knox, 1985b).

METHOD OVERVIEW

The Soil-Waste Interaction Matrix is applied in three phases.

1. Waste is classified according to toxicity, chemical behavior and application rate. This phase requires the user to obtain considerable information on the chemical properties of the waste and to make behavioral and toxicity evaluations based on commonly accepted reference material (i.e., Pavoni et al., 1972, and Sax, 1969). Some laboratory testing may be required.

2. The site is classified according to 7 soil, hydrologic and topographic factors. The factor evaluation is based on the work of LeGrand (1964) and usually requires collection of field data.

3. Waste and soil index values from (1) and (2) above are combined in a two-dimensional matrix for evaluation. Matrices can then be compared for site suitability evaluation.

METHOD OUTPUT

The method produces a two-dimensional matrix of waste and site characteristics for each site as shown in Figure 2. Within this matrix, individual chemicals or chemical combinations can be evaluated independently or in combination with geologic variables. Similarly, geologic variables can be evaluated independently or in combination with chemical variables. Criteria are also provided which define suitability on an absolute numerical scale.

Class	1	2	3	4	5	6	7	8	9	10
			Acceptable					Unacceptable		
Waste–soil-site Point score	45–100	100–200	200–300	300–400	400–500	500–750	750–1000	1000–1500	1500–2500	> 2500

WASTE \ SOIL			SOIL GROUP		HYDROLOGY GROUP			SITE GROUP		
			Permeability NP (2½-10)	Sorption NS (1-10)	Water Table WT (1-10)	Gradient NG (1-10)	Infiltration NI (1-10)	Distance ND (1-10)	Thickness of Porous Layer NT (1-10)	Total
		P*	5	4	5	2	6	7	0	29
EFFECTS GROUP	Human Toxicity Ht (0-10)	8	40	32	40	16	48	56		232
EFFECTS GROUP	Groundwater Toxicity Gt (0-10)	5	25	20	25	10	30	35		145
EFFECTS GROUP	Disease Transmission Potential DP (0-10)	0								
BEHAVIOURAL GROUP – Behavioural Performance Subgroup	Chemical Persistence Cp (1-5)	3	15	12	15	6	18	21		87
BEHAVIOURAL GROUP – Behavioural Performance Subgroup	Biological Persistence Bp (1-4)	4	20	16	20	8	24	28		116
BEHAVIOURAL GROUP – Behavioural Performance Subgroup	Sorption So (1-10)	5	25	20	25	10	30	35		145
BEHAVIOURAL GROUP – Behavioural Properties Subgroup	Viscosity Vi (1-5)	2	10	8	10	4	12	14		58
BEHAVIOURAL GROUP – Behavioural Properties Subgroup	Solubility Sy (1-5)	1	5	4	5	2	6	7		29
BEHAVIOURAL GROUP – Behavioural Properties Subgroup	Acidity/ Basicity Ab (0-5)	1	5	4	5	2	6	7		29
CAPACITY-RATE GROUP	Waste Application Rate Ar (1-10)	4	20	16	20	8	24	28		121
	Total	33	165	132	165	66	198	231		957

* P = point score

Figure 2. Soil-Waste Interaction Matrix
Source: Phillips et al. (1977)

DATA REQUIREMENTS

Data required for the evaluation are divided into two categories: waste factors and site factors.

1. Waste factors:
   a) Human toxicity (after Pavoni et al., 1972 and Sax, 1969).
   b) Ground water toxicity (after Pavoni et al., 1972).
   c) Disease transmission potential (after Pavoni et al., 1972).
   d) Chemical persistence of the waste is empirically determined by testing the specific soil involved. A 50%-by-weight mixture of soil and waste is prepared and the concentration of waste within the column is measured at one and six days. Persistence is estimated using a pseudo-first order rate constant.

e) Biological persistence of the waste is estimated using standard measurements of Biochemical Oxygen Demand (BOD) and Theoretical Oxygen Demand (TOD)(mg/l).
f) Sorption of the waste is estimated using the one-day data from the persistence test outlined in (D) above.
g) Viscosity of the waste (centipoises).
h) Solubility of the waste in pure water (25°C, pH 7).
i) pH of waste.
j) Waste application rate (quantity per unit area per unit time).

2. Site factors:
   a) Permeability based on qualitative textural classifications after LeGrand (1964).
   b) Sorption based on qualitative classifications after LeGrand (1964).
   c) Depth to water table (seasonal maximum and minimum in feet).
   d) Water table gradient (%) and direction of flow (toward or away from site).
   e) Infiltration rate.
   f) Distance from the site to the nearest point of water use.
   g) Depth to bedrock.

LIMITATIONS OF THE METHOD

1. The site evaluation incorporates factor scales from LeGrand (1964) and is subject to the same limitations.

2. The method is data intensive (17 total factors) and usually applied only to small areas.

3. Soil organic matter, an important factor in organic waste attenuation, is not specifically evaluated.

4. The group of factors which estimates human and environmental effects are based on subjective judgments -- particularly the index of disease transmission potential.

5. The chemical persistence factor is determined using a pseudo-first order rate constant which is not accurate in all situations.

Primary source: Phillips et al. (1977). *Secondary sources:* Canter and Knox (1985b), Canter et al. (1987), LeGrand (1964), Pavoni et al. (1972) and Sax (1969).

1.2 DEGRADABLE AND NON-DEGRADABLE WASTES

1.2.1 LeGRAND (1983)

GENERAL PURPOSE

The LeGrand (1964) method was originally developed as a screening method to evaluate contamination potential of waste sites prior to intensive investigations. The 1983 version is expanded to include a management control system for use by regulatory agencies and owner/operators of waste disposal facilities during planning and operational stages of contaminant handling.

The system provides a first-round evaluation of pollution potential from waste disposal sites. Hazardous waste sites are included. It provides a consistent, standardized means of evaluating sites for landfills, waste lagoons and septic systems using existing data. The method can also be used for quick appraisals of spills, leaks, pollution potential of stockpiles of highway salts, mining and radioactive wastes.

The LeGrand system is especially suited for point sources, but can also be applied to line sources (e.g., leakage from sewer lines) and non-point sources (e.g., agricultural chemicals).

SCALE

This method is usually applied to individual sites, but it can be applied to larger areas.

METHOD OVERVIEW AND DATA REQUIREMENTS

The LeGrand method is a numerical rating system consisting of four stages and 10 steps as outlined below.

Stage 1--Hydrogeologic description of the site. Includes seven steps:

Step 1. Estimate distance from contamination source to the nearest well, surface stream or property boundary (scales given for meters and feet).

Step 2. Estimate depth of water table (scales for meters and feet).

Step 3. Estimate water table gradient (%).

Step 4. Estimate type of earth materials.
a) clay
b) clay with no more than 50% sand
c) sand with 15-30% clay
d) sand with less than 50% clay
e) clean, fine sand
f) clean gravel or coarse sand

Step 5. Estimate degree of confidence that factor values are accurate (letter ratings A,B & C).

Step 6. Add letter identifiers for special site features not accounted for in the factor rating. These include:
a) miscellaneous special conditions
b) contamination source is within the sphere of influence of a pumping well
c) distance to point of use is recorded from a water supply to the edge of an existing plume rather than a contamination source
d) contamination source is in a discharge area
e) site is located on karst or fractured limestone
f) water table mounding exists beneath a site
g) inadequate percolation exists at the site for reasons other than soil permeability
h) contamination source is located in a recharge area
i) radial flow from a high water table is occurring
j) water table is in fractured rock
k) artesian aquifers underlie the water table aquifer

Step 7. Combine steps 1-6 to obtain a total site score (see *Method Output*).

Stage 2--Estimate degree of seriousness of hazard potential.

Step 8. Derived from matrix provided in the manual. No new information is required.

Stage 3--Estimate relative probability of contamination.

Step 9. Compares site index value with a standard value for comparison in a matrix format provided in the manual. No new information is required.

Stage 4--Site reassessment with engineering considerations

Step 10. Guidelines provided in the manual. No new information is required.

METHOD OUTPUT

This method produces an index score for a site that can be compared to scores from other sites as shown in Figure 3.

LIMITATIONS OF THE METHOD

1. The system is only useful on water table aquifers. It is not applicable on confined or artesian aquifers.

2. Although the system is designed to be standardized, evaluations in Step 8 are subjective in nature and may not be consistent among users.

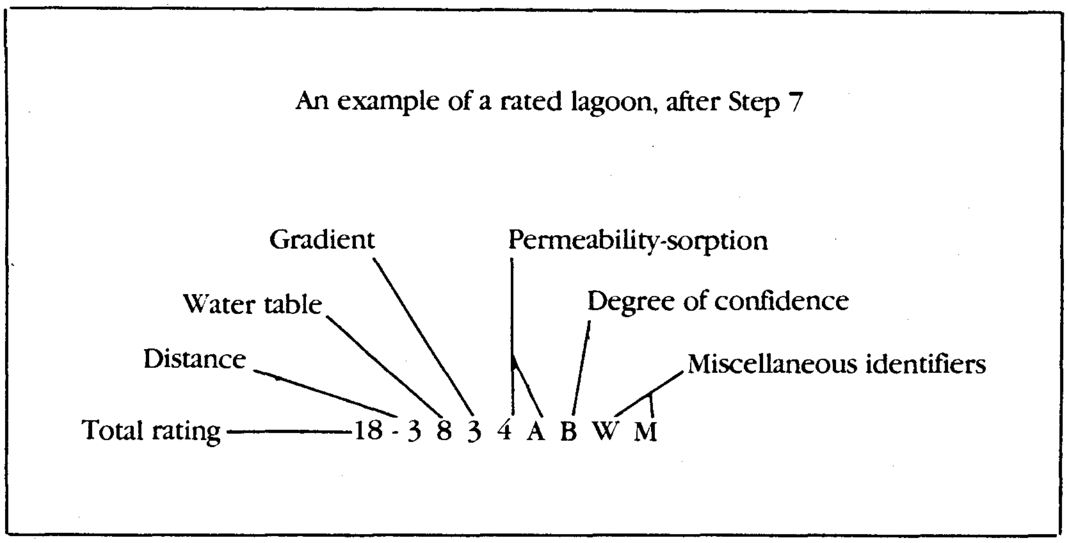


Figure 3. LeGrand Final Site Score
Source: LeGrand (1983)

Primary source: LeGrand (1983). *Secondary source:* LeGrand (1964).

1.2.2 HAZARDOUS WASTE/LANDFILL SITE RANKING SYSTEM

GENERAL PURPOSE

The Hazardous Waste/Landfill Site Ranking System is designed to compare and rank potential sites for land disposal of either hazardous or non-hazardous wastes. It is more site-specific, data-intensive and rigorous than most other screening methodologies. The final index score includes both site and waste factors in its evaluation.

SCALE

This method is designed for use on individual sites.

METHOD OVERVIEW

This methodology consists of two separate processes: a hazardous waste ranking and a landfill site ranking. Landfill site and hazardous waste factors are scored and ranked independently. Scores can then be evaluated either together or separately as follows:

1. The site index can be used independently to compare various potential sites if waste characteristics are not known or considered important.

2. The waste index can be used independently to compare different types of waste material.

3. The site and waste indices can be combined to produce an overall index which estimates the suitability of a particular site for a particular waste.

The hazardous waste ranking system ranks individual wastes according to pollution potential by evaluating five waste parameters: human toxicity, ground water toxicity, disease transmission potential, biodegradability, and mobility. Information required for this phase can be obtained from published materials.

The landfill site ranking process rates site characteristics for susceptibility to contamination. Considerable field sampling and lab data analysis are required in addition to data from existing sources. More details are given below.

METHOD OUTPUT

This method produces an index score for a site that can be compared to scores from other sites.

DATA REQUIREMENTS

Phase 1--Hazardous Waste Ranking System

1. **Human Toxicity.** The human toxicity factor is defined as "the ability of a substance to produce injury once it reaches a susceptible site in or on the body" (Hagerty et al., 1973). This factor score uses toxicity values from Sax (1969) which provides quantitative toxicity ratings for approximately 10,000 materials.

2. **Ground Water Toxicity.** The ground water toxicity factor is defined as "the critical concentration ... at which damage or injury may be caused to any portion of the ecosystem" (Hagerty et al., 1973). It is defined in terms of human toxicity, aquatic toxicity and plant toxicity. The user must obtain estimates of these values from standard literature sources as discussed in the methodology.

3. **Disease Transmission Potential.** Although potentially important, this factor could not be quantified when this method was developed. Consequently, arbitrary values were assigned based on transmission properties of the medium. To estimate disease transmission potential, the user must obtain information on:
   a) Mode of disease transmission (i.e., whether disease is spread through direct contact, open sores, or vectors such as mosquitoes or flies).
   b) Life-cycle of the pathogen.
   c) Ability of the pathogen to survive in various environments including land, air and water.

4. **Biological Persistence of the Waste.** Biodegradability estimates are based on:
   a) Biochemical Oxygen Demand (BOD mg/l).
   b) Theoretical Oxygen Demand (TOD mg/l).

5. **Waste Mobility.** Estimated using:
   a) Net electrical charge of a waste at pH 7.0.
   b) Solubility (mg/l).

Phase 2--The Landfill Site Ranking System:

1. **Infiltration Potential** -- estimated using:
   a) Precipitation estimates from rainfall intensity graphs (inches).
   b) Volumetric field capacity expressed as a decimal.
   c) Thickness of the soil cover layers (inches).

2. **Bottom Leakage Potential** -- estimated using:
   a) Bottom soil permeability (cm/sec).
   b) Bottom soil thickness (feet).

3. **Filtering Capacity** -- estimated using average soil particle diameter (inches).

4. **Adsorptive Capacity** -- estimated using soil cation exchange capacity (CEC in milliequivalents of monovalent cations exchanged per 100 grams of soil).

5. **Organic Matter Content of the Ground Water** (%) -- estimated using BOD. Must be determined by field sampling.

6. **Buffering Capacity of the Ground Water** (milliequivalents) -- estimated by determining the smallest number of milliequivalents of either an acid or base that will displace the original ground water pH below 4.5 or above 8.5. Must be determined experimentally.

7. **Travel Distance** (feet or miles) -- taken from the point directly below the landfill through ground and surface water systems to point of use.

8. **Ground Water Velocity** -- estimated using:
   a) Coefficient of permeability (k) of the soil (cm/sec).
   b) Slope of the water table (ft/mile).

9. **Prevailing Wind Direction** -- estimated within a 25-mile radius from the site.

10. **Population density and distribution** -- within 25 miles of the site.

LIMITATIONS OF THE METHOD

While this method incorporates significant amounts of data into an extensive analysis, it has some limitations.

1. The method does not address chemicals with detectability/toxicity ratios greater than 1.0. It assumes that highly toxic chemicals that are not easily detected in field situations will not even be considered for landfill disposal.

2. Materials with flashpoints lower than normal air temperatures are not considered.

3. Many parameters used in the estimate are based on inadequate data and subjective judgment which could introduce substantial error. For example, the disease transmission potential is based solely on broad groupings of pathogen characteristics.

4. Much of the data required is not readily available. For example, field testing of prospective sites is needed for determining ground water BOD and buffering capacity.

Primary sources: Hagerty et al. (1973) and Pavoni et al. (1972). *Secondary source:* Canter et al. (1987).

1.3 INDUSTRIAL SURFACE IMPOUNDMENTS

1.3.1 SURFACE IMPOUNDMENT ASSESSMENT METHOD (SIA)

GENERAL PURPOSE

The Surface Impoundment Assessment Method (SIA) was designed to estimate relative ground water contamination potential among industrial surface impoundment sites (e.g., pits, ponds and lagoons). The SIA has also been used to estimate pollution potential for single or multiple septic systems (Canter and Knox, 1985b).

The SIA is an inexpensive, first-round evaluation designed to optimize resource allocation for site remediation. It compares the pollution potential of different sites based on geological and chemical variables so that money for more detailed investigations can be better allocated.

Because SIA is a first round evaluation, precise data is not required. Estimates can be made on the best information available and confidence intervals determined.

SCALE

The SIA method is site-specific. However, it has been used in subdivisions containing several hundred individual septic systems (Canter and Knox, 1985b).

METHOD OVERVIEW

The evaluation is accomplished in two phases: 1) rating of actual ground water contamination potential of the site; and, 2) rating relative magnitude of "potential endangerment" to current users of underground drinking water sources. Data can be gathered from existing information--field sampling is not required. The process involves nine steps as outlined below:

Step 1. **Rating the Unsaturated Zone.** Using topographic maps or well logs, the user must determine the approximate thickness of the unsaturated zone and the type of earth material in that zone. Soil and geologic information are incorporated.

Step 2. **Rating Ground Water Availability** (saturated zone). Parameters used in this step are the same as in (1) above but rated differently to give comparisons of aquifers based on yield.

Step 3. **Rating Ground Water Quality.** The user must obtain an estimate of Total Dissolved Solids (TDS) of the ground water. The TDS measurement is used as an estimate of ambient ground water quality to help determine the water use for which the aquifer is best suited.

Step 4. **Rating Waste Hazard Potential.** The user must know both the sources and types of contaminants involved. However, knowledge of specific chemical properties of contaminants is not required. Contaminant sources are ranked according to the Standard Industrial Classification (SIC). Contaminant types are ranked according to standard EPA classifications.

Step 5. **Determining the Site's Overall Contamination Potential.** Factors 1-4 are combined to produce an overall index. No new is information required.

Step 6. **Determination of Endangerment to Current Water Supplies.** The user must determine the distance from the impoundment site to the source of drinking water. The user must also determine the direction of ground water flow within one mile of the site. This information is usually taken from a 7.5 minute topographic map.

Step 7. **Determination of Investigator's Degree of Confidence.** Based on the sources of information used by the investigator, a confidence level is estimated. The more precise the estimates (i.e., field data, well logs), the higher the rating.

Step 8. **Incorporation of Identifiers.** Identifiers are incorporated into the score to represent important variables not explicitly rated in the system (e.g., karst, recharge area, existing contamination).

Step 9. **Final Site Evaluation.** See *Method Output.*

METHOD OUTPUT

The SIA method produces a standardized evaluation for each site. The site information from steps 1-8 is incorporated into a layered index format for comparison with other candidate sites as shown in Figure 4.

DATA REQUIREMENTS

1. Earth Materials
   a) Unconsolidated Rock -- particle size classification
      i. Gravel, coarse to medium sand.
      ii. Fine to very fine sand.
      iii. Sand with <15% clay or silt.
      iv. Sand with >15% but <50% clay.
      v. Clay with <50% sand.
      vi. Clay.

9	C	A	4	C	A	5	A	3	B	2	1	8	B	B	R	F	
	Unsat. Zone	Confidence		G. W. Avail.	Confidence	G. W. Qual.	Confidence	Waste	Confidence	G. W. Poll. Potential		Health Hazard		Confidence	Miscellaneous Identifiers		
STEP 1			STEP 2			STEP 3		STEP 4		STEP 5		STEP 6					

Figure 4. Index Format for the Surface Impoundment Assessment Method
Source: Silka and Swearingen (1978)

b) Consolidated Rock -- structural information
   i. Cavernous or fractured limestone, evaporites, basalt lava, fault zones.
   ii. Fractured igneous and metamorphic rock, poorly cemented sandstone.
   iii. Moderately cemented sandstone, fractured shale.
   iv. Well-cemented sandstone.
   v. Siltstone.
   vi. Shale.
c) Permeability (cm/sec) -- representative ranges are provided for earth materials.
d) Thickness of the unsaturated zone based on seasonal high water table.

2. Ground Water Availability -- same parameters as (1) above *except* rating is done for saturated zone.
3. Ground Water Quality -- Total Dissolved Solids (TDS) in mg/l.
4. Waste Hazard Potential
   a) Contaminant source.
   b) Contaminant type.
5. Determination of overall score -- sum of scores from 1-4 above.
6. Potential Endangerment
   a) Distance from impoundment to drinking water source (ground or surface).
   b) Direction of ground water flow within one mile of impoundment.

LIMITATIONS OF THE METHOD

1. The SIA rating evaluates only the contamination potential of a site relative to other sites. It does not provide an absolute scale of contamination potential for a particular site. Such determination requires site-specific evaluation.
2. When used in evaluating septic systems, the SIA method does not account for waste water flow, an important factor in waste water attenuation.
3. This method is only useful for assessing existing contaminated sites unless the exact types and sources of potential contamination are known.

Primary source: Silka and Swearingen (1978). *Secondary sources:* Canter and Knox (1985a), Canter et al. (1987) and Trojan (1986).

SECTION 2: SITE REMEDIATION RANKING

Site remediation methodologies are designed to rank existing waste sites according to ground water pollution potential. The EPA Hazard Ranking System, perhaps the most widely known, is extensively used to rank hazardous waste sites for Superfund cleanup.

Methodologies in this section are generally complex, requiring extensive data and professional expertise in their application. For example, the Site Rating Methodology (Kufs et al., 1980) evaluates 31 factors in four categories: receptors, pathways, waste characteristics, and waste management. The EPA Hazard system and related methodologies evaluate contamination potential via surface water routes, ground water routes, air migration routes, fire/explosion potential, and direct contact hazards.

Site remediation methodologies generally require information in four general categories: 1) soils/hydrogeology, 2) waste characteristics and quantity, 3) population affected, and 4) condition and maintenance of containment structures. With the exception of the Geologic Ranking System, these methodologies are site-specific.

The techniques reviewed here are organized from simplest to most detailed in the following sub-categories:

1. Screening methodologies for ranking large numbers of abandoned dump sites over large geographic areas according to hydrogeologic criteria only.
   a) Geologic Ranking System

2. Methodologies which rank ground water pollution potential and human exposure.
   a) Ground Water Contamination Site Ranking Methodology
   b) New Jersey Ground Water Pollution Priority System

3. Methodologies which evaluate contamination to ground water, human exposure, and environmental hazards.
   a) Kansas Ranking System
   b) Site Rating Methodology

4. Comprehensive methodologies that rate contamination potential according to ground water routes, surface water routes, air routes, fire/explosion hazard, and human exposure.
   a) EPA Hazard Ranking System
   b) Michigan Site Assessment System

The Michigan Site Assessment System is a variation of EPA Hazard. They are the most complex, data-intensive methodologies if all migration routes (ground water, surface water, air, fire/explosion, direct contact) are considered. Other methods are also complex, but address only ground water migration routes. The Geologic Ranking System is the simplest method, incorporating only hydrogeologic factors.

2.1 SCREENING LARGE ABANDONED DUMP SITES

2.1.1 GEOLOGIC RANKING SYSTEM

GENERAL PURPOSE

The Geologic Ranking System was developed to help managers locate, classify and rank abandoned dump sites for cleanup. It is designed to evaluate large numbers of sites over large geographic areas where information is scarce or difficult to locate. The method is suited for managers or government agencies that wish to minimize costs by locating and prioritizing sites for more detailed investigation. The Geologic Ranking System is a screening tool to precede more detailed, site-specific methods.

SCALE

This method is designed for use on counties, townships, or regional areas.

METHOD OVERVIEW

The Geologic Ranking System involves four basic steps. The following is a brief description of each step:

1. **Initial site identification** -- requires a general reconnaissance survey of the area under consideration using existing data such as aerial photographs, health department records and government publications on hazardous waste sites. After sites are located, the type of waste disposal activity on these sites is classified into 6 categories including dumping, filling, waste lagoons, junk yards, unspecified areas and "suspicious" areas. A site activity record is compiled for each site.

2. **Geologic analysis** -- performed using map overlays to identify important geologic and hydrogeologic components which influence production, containment and behavior of leachate. Geological information involving the ground water system, soil and rock permeability, and hydrogeology is needed. Sites are then ranked using work sheets provided with the methodology.

3. **Incorporation of well location** -- used to evaluate risk to the nearest point of use, i.e., public or private wells.

4. **Development of a final score** -- sums factor scores from steps 1-3 into a ranking of potential sites.

METHOD OUTPUT

The final product of this methodology is a numerical ranking for each site.

DATA REQUIREMENTS

Because of its broad application at large spatial scales, this methodology does not require field data. It does not identify site contents. Considerable professional judgement and expertise is needed to interpret the results because explicit indexed values are not given for all of the factors. Information required includes:

1. General geologic information such as aerial photographs, geologic and hydrogeologic maps, county soil maps and atlases.
2. Locations of public and private wells in relation to dump sites.
3. Land use in the vicinity of the site.
4. Overburden geology.
5. Soil permeability.
6. Relief, geomorphology.
7. Depth to ground water (ft).
8. Ground water gradient (%).
9. Bedrock character.
10. Soil properties, texture and behavior.

LIMITATIONS OF THE METHOD

1. Use of this system requires considerable professional judgement by someone with hydrogeologic training. While specific factors such as soil texture and permeability are considered, explicit indexed values are not given for all of the factors. Factor ranking and index development is based on the professional judgement of the user. Since uniform guidelines are not clearly established, transfer of information among users or agencies can be difficult.

2. The method is purely geologic in scope. No formal consideration is given to specific contaminants and their behavior.

3. The method is not appropriate for site specific analyses because of limited data input.

Primary source: Nelson and Young (1981).

2.2 GROUND WATER CONTAMINATION POTENTIAL AND HUMAN HEALTH HAZARD

2.2.1 GROUND WATER CONTAMINATION SITE RANKING METHODOLOGY

GENERAL PURPOSE

This method estimates relative ground water contamination potential of existing hazardous waste sites. It ranks site potential relative to other sites and contaminant severity on an absolute scale. It is designed to rank the threat to ground water based on limited data. Key objectives outlined by the procedure include:

1. Optimize use of existing data.
2. Concisely describe hydrogeologic site conditions.
3. Concisely describe the extent of soil and ground water contamination.
4. Relate hydrogeologic site conditions and the severity of contamination.
5. Identify data uncertainty and target areas for further investigation.
6. Put the hazard potential of a site in perspective.

SCALE

The Ground Water Contamination Site Ranking method is designed for use on individual sites.

METHOD OVERVIEW

This method ranks contamination potential in three distinct sections: 1) site sensitivity ranking, 2) contaminant severity ranking, and 3) integration of (1) and (2) above. The methodology first identifies and assigns values to physical and chemical factors associated with contaminated sites. It then integrates factor scores into one of two risk assessment analyses: a numerical site score composed of summed factor values or a two-dimensional matrix for graphic representation (see *Method Output* below).

DATA REQUIREMENTS

Most hydrogeologic data used in this method can be gathered from existing sources such as maps and government records. Some contaminant data from the actual site are required.

1. **Site Sensitivity Ranking.** Six factors evaluated as follows:

   a) Distance from site to point of use (meters) measured to:
      i. Public wells down gradient from the site.
      ii. Public wells not down gradient from the site.
      iii. Private wells down gradient from the site.

   b) Intensity of water use based on:
      i. Well production by township section (1000 m^3).
      ii. Number of public wells less than 475 meters (1500 feet) down gradient from the site.
      iii. Number of private wells less than 2.6 km^2 (one square mile) down gradient from the site.
      iv. Number of public wells between 1500 feet and one square mile down gradient from the site.

   c) Depth to water table (meters) described as:
      i. Shallowest ground water.
      ii. Shallowest useable ground water.
      iii. Shallowest potable ground water.

   d) Permeability (meters/day) for 3 depth ranges:
      i. 0-15 meters
      ii. 15-46 meters
      iii. 46-91 meters

      Typical permeability values are provided for six classes of earth material ranging from gravel to clay.

   e) Number of abandoned wells within 2.6 km^2 (one square mile) of the site.

   f) Water table gradient (%).

Figure 5 shows graphical representations of factor scores.

2. **Contamination Severity Rating.** Field data collection is required for some factors.

   a) Acute toxicity (3 categories):
      i. Oral LD50 (mg/kg)
      ii. Dermal LD50 (mg/kg)
      iii. Aquatic LC50 (mg/kg)
      iv. Carcinogenicity
      v. Mutagenicity.

      Rating scales are provided for each category in the manual. Sources for (iv) and (v) above include government publications, reference manuals, and open literature.

   b) Physical/chemical properties as shown in Figure 6:
      i. Octanol/water partition coefficient (K_{ow}).
      ii. Soil sorption constant (K_{sc}).

   c) Magnitude of contamination as shown in Figure 6.
      i. Highest contamination measured in ground water or soil (ppm).
      ii. Longest dimension between non-detectable levels along water table gradient.
      iii. Number of chemicals present.

3. **Ranking Procedure** involves integration of scores from (1) and (2) above. No new data is required.

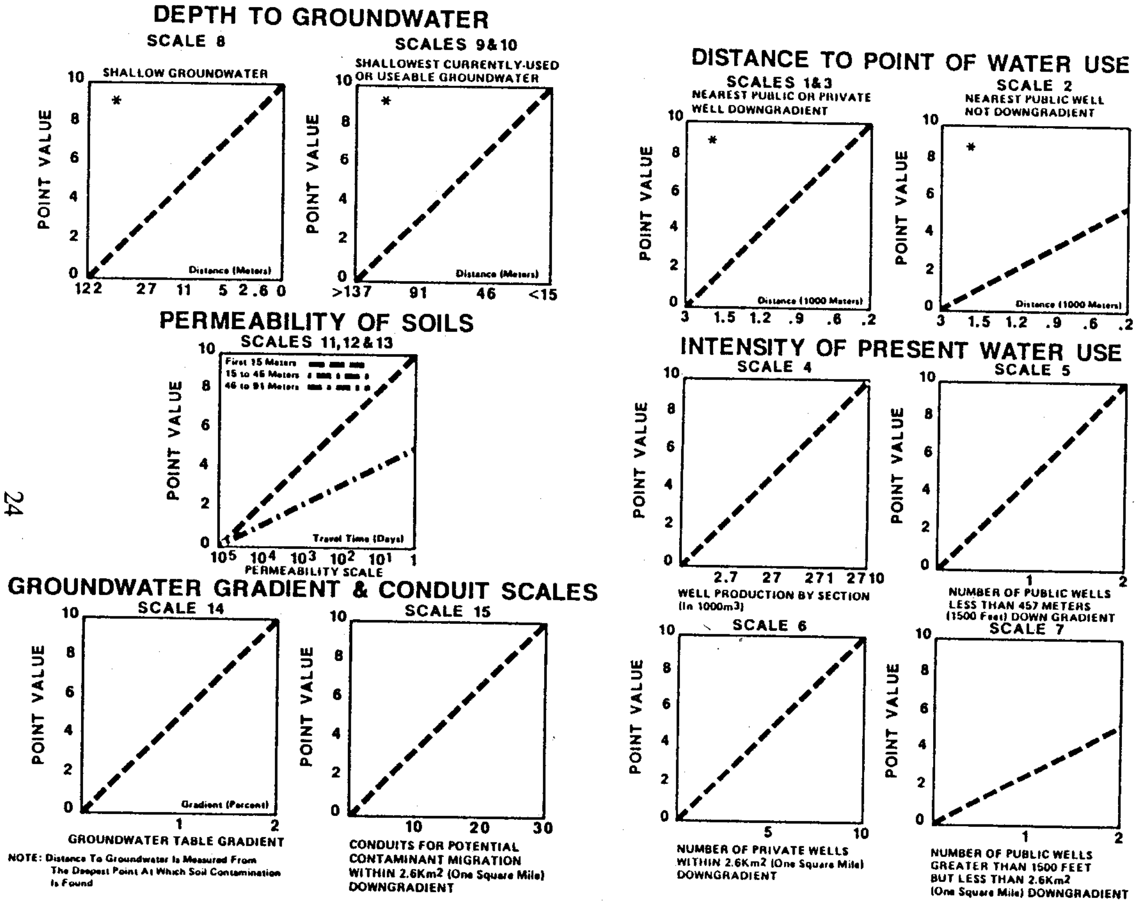


Figure 5. Ground Water Contamination Site Ranking Methodology: Graphical Representation of Factor Scores
Source: Olivieri et al. (1986)

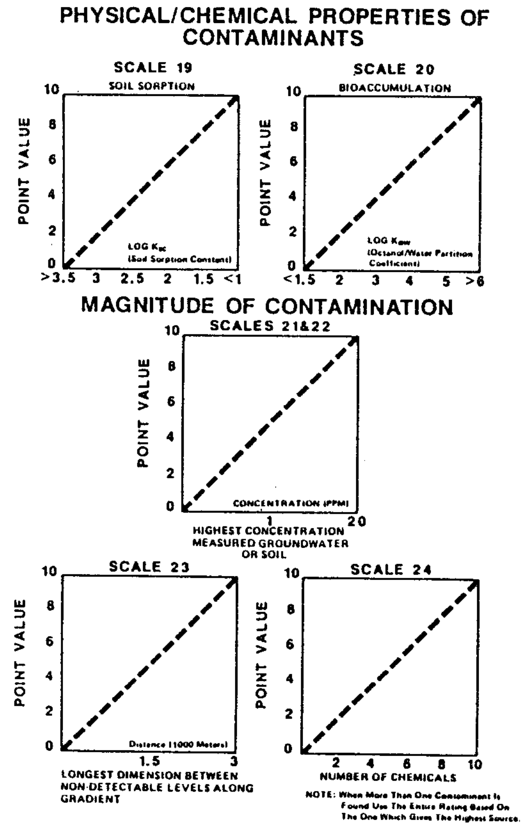


Figure 6. Ground Water Contamination Site Ranking Methodology: Physical/Chemical Properties of Contaminants
Source: Olivieri et al. (1986)

METHOD OUTPUT

Two outputs can be generated from this method: a numerical site index for relative comparison among sites or a risk potential matrix as shown in Figure 7.

LIMITATIONS OF THE METHOD

1. This ranking system is not as rigorous as other site assessment methods (e.g., EPA Hazard and Michigan Site Assessment System). Alternative contaminant pathways such as air, surface water, fire, and explosion hazard are not included.

2. The system is only useful on water table aquifers. It is not applicable on confined or artesian aquifers.

3. Carcinogenicity and mutagenicity ratings are derived from public health data that is not well-established at this time. Consequently, ratings can be subjective and uncertain. While acute toxicity data is fairly well-established, chronic toxicity ratings can still be controversial (Olivieri et al., 1986).

4. Estimates of chronic contaminant effects such as reproductive impairment, physiological dysfunction, or other potential organ damage are not included.

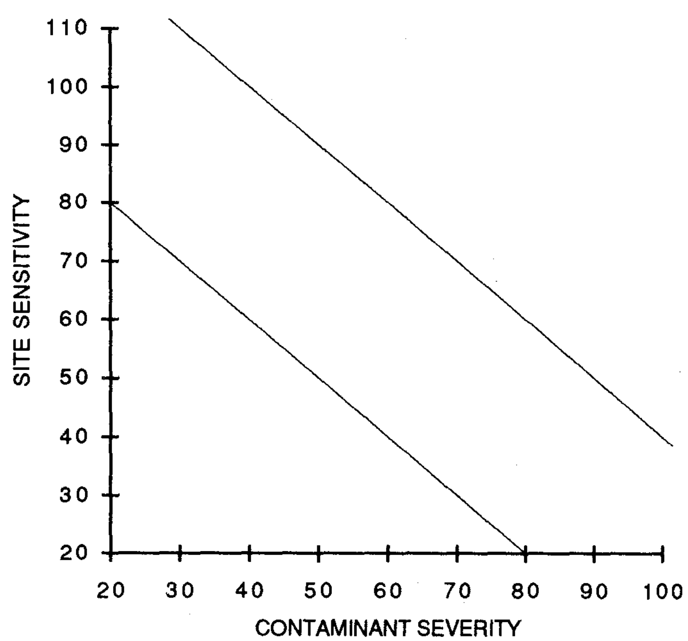


Figure 7. Ground Water Contamination Site Ranking Methodology Risk Potential Matrix
Source: Olivieri et al. (1986)

Primary source: Olivieri et al. (1986).

2.2.2 NEW JERSEY GROUND WATER POLLUTION PRIORITY SYSTEM

GENERAL PURPOSE

The New Jersey Ground Water Pollution Priority System evaluates pollution potential of individual waste sites to ground water quality. The system can be used to evaluate relative risks among different sites or evaluate site hazard on an absolute scale. Waste characteristic, health risk, target population and similar rankings are included making the system applicable to both hazardous and non-hazardous sites.

SCALE

This method is designed for use on individual sites.

METHOD OVERVIEW

The New Jersey system incorporates 19 factors into its evaluation. Eleven factors describe site characteristics and eight factors describe chemical characteristics. Severity of contamination potential for each factor is rated from 0 to 3 according to criteria described in the method. Each factor score is then assigned a weight according to its importance and a final score is determined. There are 7 steps for rating the potential hazard of a site:

1. **Locate and identify the site** using the work sheet provided in the method. Includes name, address and other identifying features.

2. **Compile background information**: existing information is acceptable, but the manual recommends specific site data. A list of available information sources is provided in the manual.

3. **Resolve missing data problems** according to specific guidelines outlined in the manual. Certain "non-critical" factors can be eliminated from the analysis making the procedure flexible. However, the method defines four critical factors relating to toxic substances which must be included in the evaluation. These include:
   a) the diversity of highly toxic chemicals present
   b) contaminant toxicity
   c) radioactivity
   d) persistence

   The total site score cannot be calculated if any of these critical factors are absent.

4. **Rate scale levels** according to guidelines specified in the manual.

5. **Rate factor scores** according to multipliers provided in the manual.

6. **Determine group subscores** for both site and contaminant.

7. **Determine overall site score.**

METHOD OUTPUT

This method produces a site index which can be either compared to other sites for evaluation or used as an estimate of site hazard on an absolute scale. The method provides an easy-to-use work sheet as shown in Figure 8, and an "Overall Hazard Potential Score" for determining the level of potential hazard from an individual site as shown in Figure 9.

NAME OF SITE ______________________ ACTIVE INACTIVE ABANDONED (circle one)
LOCATION ______________________ LAT. ___° ___' ___" LONG ___° ___' ___"
OWNER / OPERATOR ______________________
ADDRESS ______________________
PREPARER ______________________ DATE ______________

	RATING FACTOR	SOURCE AND BASIS OF INFORMATION	RATING SCALE LEVEL (CIRCLE ONE)				MULTI-PLIER	FACTOR SCORE	MAX. SCORE
1 a.	Distance to nearest downgradient well		0	1	2	3	12		36
1 b.	Distance to nearest side-gradient well		0	1	2	3	10		
1 c.	Distance to nearest upgradient well		0	1	2	3	6		
2a	Downstream distance to nearest potable surface water intake		0	1	2	3	10		30
2b	Distance to nearest surface water of potable quality		0	1	2	3	6		
2c	Downgradient distance to nearest surface water		0	1	2	3	2		
3	Background ground water quality		0	1	2	3	6		18
4	Recharge		0	1	2	3	6		18
5	Unsaturated zone thickness		0	1	2	3	7		21
6	Unsaturated zone permeability		0	1	2	3	6		18
7	Saturated aquifer thickness		0	1	2	3	5		15
8	Saturated zone permeability		0	1	2	3	6		18
9	Hydraulic gradient		0	1	2	3	6		18
10	Depth to bedrock		0	1	2	3	3		9
11	Population endangered by aquifer problem		0	1	2	3	8		24
	Site	SCORE SUMS							
12.	Source duration		0	1	2	3	5		15
13.	Number of highly toxic chemicals and known or suspected carcinogens		0	1	2	3	5		15
14.	Toxicity		0	1	2	3	8		24
15	Gross alpha radioactivity		0	1	2	3	7		21
16.	Persistence		0	1	2	3	5		15
17.	In-situ mobility		0	1	2	3	5		15
18.	Hazardous waste quantity		0	1	2	3	7		21
19.	Total waste quantity		0	1	2	3	5		15
	Waste	SCORE SUMS							

Group Subscore = Factor Score / Max. Possible Score X 100

Number of Missing and Assumed Values (out of 19) =

Percentage of Missing and Assumed Values =

Site Subscore =

Waste Subscore =

Waste & Site Factor Scores / Combined Max Possible Score X 100 = Overall Site Score =

Figure 8. Work Sheet for the New Jersey Site Assessment
Source: Hutchinson and Hoffman (1983)

0 10 20 30 40 50 60 70 80 90 100

Very low Low Moderate High Very High

Generalized Level of Potential Hazard

Figure 9. New Jersey Overall Hazard Potential Score
Source: Hutchinson and Hoffman (1983)

DATA REQUIREMENTS

Eleven Site Factors:

Factor 1. Distance to nearest active well (feet) in three directions from pollution source:
a) downgradient
b) on the side of steepest hydraulic gradient
c) upgradient

Factor 2. Distance to the nearest surface water or reservoir (feet).

Factor 3. Background water quality defined as non-potable due to human causes, non-potable due to natural causes, marginally potable, and potable.

Factor 4. Recharge (inches/year) actually moving through contamination site. Not simply average annual precipitation.

Factor 5. Unsaturated zone thickness (feet) measured from bottom of landfill, dump, impoundment or tank to the top of water table.

Factor 6. Unsaturated permeability and sorption defined according to both the USDA soil classification and Unified Soil Classification System.

Factor 7. Saturated aquifer thickness (feet).

Factor 8. Saturated zone permeability defined according to soil classification.

Factor 9. Hydraulic gradient (%) in direction of active wells or surface water.

Factor 10. Depth to bedrock (feet) considering degree of fracture.

Factor 11. Population served by endangered aquifer (number of people).

Eight Waste Factors

Factor 1. Time of source existence (years) measured from date of initial deposit.

Factor 2. Diversity of highly toxic chemicals present rated according to four classifications:
a) 0-1
b) 2-5
c) 6-10
d) >10

Factor 3. Toxicity based on Sax (1969). Ratings provided for selected chemicals in manual.

Factor 4. Radioactivity (picocuries).

Factor 5. Persistence rated according to four classifications:
a) Nonpersistent; easily biodegradable
b) Low persistence; straight chain hydrocarbons
c) Moderate persistence; substituted and other ring hydrocarbons
d) Highly persistent; metals, polycyclic compounds, halogenated hydrocarbons, and conservative compounds
Persistence ratings are given for many chemicals in the manual.

Factor 6. In situ mobility rated according to four classifications:
a) Immobile
b) Low mobility
c) Moderate mobility
d) High mobility
Tables in the manual provide mobility estimates for selected chemicals.

Factor 7. Hazardous waste quantity present in either English or metric units.

Factor 8. Total waste quantity present in either English or metric units.

LIMITATIONS OF THE METHOD

1. Unlike other methods for evaluating hazardous waste sites, the New Jersey system considers only ground water contamination risk, not total environmental risk. Surface water routes, air routes, fire and explosion hazard are excluded.

2. Organic matter, a major factor in contaminant attenuation, is not included. Only contaminant mobility is considered.

3. The method is very site-specific.

Primary source: Hutchinson and Hoffman (1983). *Secondary source:* Trojan (1986).

2.3 GROUND WATER CONTAMINATION POTENTIAL, HUMAN HEALTH HAZARDS, AND ENVIRONMENTAL HAZARDS

2.3.1 KANSAS RANKING SYSTEM

GENERAL PURPOSE

The Kansas Ranking System is a an expanded version of EPA DRASTIC (see *Section 3.1.1*). It is designed as a screening tool to rank existing contamination sites for remediation. It is intended to help managers allocate resources for detailed investigations of newly discovered sites.

SCALE

The method is designed for a nine township section (9 square mile) area. If a contamination site is found in one particular township, the methodology evaluates conditions in that particular township plus the eight townships adjacent to it.

METHOD OVERVIEW AND DATA REQUIREMENTS

As in DRASTIC, the Kansas methodology takes into account water use and public risk. The ranking system requires eight categories of site information including:

1. resource use
2. distance to point of exposure
3. number of public water supplies
4. contamination type and relative concentration
5. aquifer vulnerability to contamination
6. population density around contamination site
7. environmental effects
8. availability of ground water

Each category is ranked according to specified criteria and multiplied by a weighting factor. The resulting rankings are summed to obtain a final site score.

Procedure

When a new site is identified, the following process is used to determine the site index.

1. Choose the condition most appropriate for the site within each category (1-8 below).
2. Determine the appropriate rating and multiply by the weighting factor.
3. Add each of the weighted ratings to obtain the priority ranking number for the site.
4. Compare the priority ranking number to other site rankings.

Since this is a screening technique, information can usually be gathered from existing sources. The following is a brief description of each category and the information required.

1. **Resource use (U).** Choose the current, most restrictive resource use within the area. Categories include:
   a) Public water supply
   b) Private water supply

c) Environmental support (i.e., extent to which the resource in its uncontaminated state supports indigenous plant or animal life)
d) Irrigation/industrial supply
e) Unused

2. **Distance to point of exposure (D)** taken from the point of highest detected concentration to nearest point of human contact (feet). Points of exposure include wells, springs, seeps and other discharge to surface waters or human habitation. Distance categories include:
   a) 0 to 1,000 feet
   b) 1,001 to 2,000 feet
   c) 2,001 to 5,000 feet
   d) 5,001 to 10,000 feet
   e) Greater than 10,000 feet

3. **Number of public water supplies (N)** in the 9 section area. Categories include:
   a) 12 or more
   b) 9 to 12
   c) 5 to 8
   d) 1 to 4
   e) 0

4. **Contaminant type and relative concentration (C).** Ratings defined by Kansas drinking water standards are provided in the manual.

5. **Aquifer vulnerability (V)** defined by the EPA DRASTIC index. DRASTIC scores are converted to a rating scale compatible with the Kansas format.

6. **Population density (P)** for the county in which contamination occurred (persons per square mile). Categories include:
   a) 101 to 1150
   b) 51 to 100
   c) 11 to 50
   d) 6 to 10
   e) 1 to 5

7. **Environmental effects (E)**: significance of the 9 section area and effects of contamination. Includes both ecological and commercial impacts on surface water resources. This category was ranked according to guidelines specified by the Kansas Department of Health and Environment in other documents. Categories include:
   a) Outstanding -- critical habitat for endangered species
   b) High -- protected or conserved site, high priority fishery resource, or special aquatic life use standards.
   c) Good -- high or moderate priority fishery resource
   d) Average -- any classified water or rated stream (as specified by various Kansas state agencies)
   e) None -- unlisted or unclassified water

8. **Availability of ground water (A)** from the aquifer containing the contaminated site (gallons per minute). Categories include:
   a) Greater than 1000
   b) 500 to 1000

c) 100 to 500
d) 10 to 100
e) 0 to 10

METHOD OUTPUT

This method produces an area index that can be compared with other area indices.

LIMITATIONS OF THE METHOD

1. Criteria for categories (4) and (7) were developed using Kansas State guidelines. Transferring use of this technique to other states would involve either 1) extrapolating Kansas standards, or 2) developing new rating standards.

2. The Kansas methodology does not provide an absolute scale of contamination severity. It rather provides a relative comparison of various sites.

Primary source: Kansas Department of Health and Environment (1986). *Secondary sources:* Aller et al. (1985) and Trojan (1986).

2.3.2 SITE RATING METHODOLOGY

GENERAL PURPOSE

This methodology estimates pollution potential associated with existing hazardous waste facilities and ranks them for remediation.

The methodology is designed for use in both preliminary assessment and actual site investigations. Prior to site visits, ratings can be made based solely on published materials, public and private records and existing contracts to determine which sites should be visited first. Final ratings are made using information gathered from the site itself. The final rating can be used to determine how much additional sampling is needed and as an aid in developing remediation plans.

SCALE

This method is designed for use on individual sites.

METHOD OVERVIEW

The general organization of the method includes three distinct sections: 1) the Rating Factor System which rates the general hazard potential of a site, 2) the Additional Points System which modifies the rating based on site-specific problems, and 3) the Score Interpretation System which helps users interpret ratings in meaningful terms.

Section 1: The Rating Factor System involves initial rating of a site based on 31 factors which have been divided into four categories: receptors, pathways, waste characteristics, and waste management practices. Scales have been designed so that factor information can be gathered from existing records and published information. Field data collection and laboratory analysis are not required.

Section 2: The Additional Points System assigns points for special site features such as location, design or operation that cannot be handled by the rating system alone (e.g., high population densities near a site). Guidance for assigning additional points and information required is provided in the methodology.

Section 3: The Score Interpretation Section allows the user to interpret site scores in either relative or absolute terms. Relative comparisons can be made by comparing scores from various sites. An absolute score interpretation scale has also been developed to help the user determine whether or not the pollution hazard is "bad" as shown in Figure 10.

0 10 20 30 40 50 60 70 80 90 100

Very Low Low Mod. High Very High

Generalized Level of Potential Hazard

Figure 10: Site Rating Methodology Overall Hazard Score
Source: Kufs et al. (1980)

In addition, sites can be ranked in several ways including overall scores, subscores or combinations of scores providing greater flexibility and interpretive power.

METHOD OUTPUT

This method produces an index score for a site that can either be interpreted independently or compared to scores from other sites.

DATA REQUIREMENTS

Category 1: Receptors

1. Population within 1000 feet of facility
2. Distance to nearest drinking water well (miles)
3. Distance to nearest off-site building (miles)
4. Land use zoning
5. Critical environments: pristine natural areas, wetlands, floodplains, nature preserves, endangered species habitat

Category 2: Pathways

1. Evidence of contamination (indirect or verified)
2. Levels of contamination based on laboratory or site visits
3. Type of contamination including soil, biota, air, food or water
4. Distance to nearest surface water (miles)
5. Depth to ground water (feet)
6. Net precipitation (inches)
7. Soil permeability based on % clay present
8. Bedrock permeability (qualitatively rated)
   a) impermeable
   b) relatively impermeable

c) relatively permeable
d) very permeable
9. Depth to bedrock (feet)

Category 3: Waste Characteristics

1. Toxicity according to Sax ratings (guidelines provided in the methodology)
2. Radioactivity defined in terms of multiples of background levels
3. Persistence classifications (descriptive classifications)
   a) easily degradable compounds
   b) straight chain hydrocarbons
   c) substituted and other ring hydrocarbons
   d) metals, polycyclic compounds, halogenated hydrocarbons
4. Flashpoint (degrees fahrenheit or NFPA guidelines)
5. Reactivity (NFPA guidelines)
6. Corrosiveness (pH)
7. Solubility (descriptive classifications)
   a) insoluble
   b) slightly insoluble
   c) soluble
   d) very soluble
8. Volatility (vapor pressure mm of Hg)
9. Physical state (solid, sludge, liquid or gas)

Category 4: Waste Management Practices

1. Site security (e.g., fenced, guards present)
2. Hazardous waste quantity (tons)
3. Total waste quantity (acre-feet)
4. Waste incompatibility (precise meaning not specified)
5. Use of liners (clay, synthetic, concrete, or asphalt based)
6. Use of leachate collection systems (classed as adequate or inadequate)
7. Use of gas collection systems classed as:
   a) adequate
   b) collection and controlled flaring
   c) venting or inadequate
   d) no collection or treatment
8. Use and condition of waste containers (qualitatively defined)
   a) few leaky
   b) many leaky
   c) containers not used

LIMITATIONS OF THE METHOD

1. Many of the factor ratings are subjective and qualitative in nature. Differing scores could be obtained by different users.
2. The method relies heavily on existing corporate and government records regarding compliance with regulations in well construction. Inaccuracies in the information will introduce error into the estimates.

Primary source: Kufs et al. (1980). *Secondary source:* Canter (1985).

2.4 COMPREHENSIVE METHODOLOGIES

2.4.1 HAZARD RANKING SYSTEM

GENERAL PURPOSE

The Hazard Ranking System (Hazard) is designed to rank hazardous waste facilities for remedial action in terms of potential hazard to both the environment and human health. It has been used extensively in setting priorities among sites for Superfund cleanup. This system can also be used in the site selection for new facilities (Canter et al., 1987).

In contrast to most empirical ground water sensitivity assessment techniques, Hazard addresses a wider variety of problems. It produces relative index scores for: 1) potential harm to humans as a result of migration of substances from the site via surface water, ground water and air, 2) potential harm from explosions and fire, and 3) potential harm as a result of direct human contact. For the purposes of this paper, only the ground water sensitivity index will be reviewed.

SCALE

This method is designed for use on individual sites.

METHOD OVERVIEW AND DATA REQUIREMENTS

The Ground Water Migration section of Hazard requires considerable information about the facility, its surroundings, hazardous substances present, and hydrogeology of the area. Because of the detailed nature of the analysis, a multi-disciplinary team from geology, hydrology, chemistry and the ecological sciences is recommended (Caldwell et al., 1981). The following is a description of the procedure.

1. **Release of substance**. The user must first determine if actual release of contaminants has taken place. This requires field verification such as measurement of contaminant in a nearby well at greater than background levels.

2. **Route Characteristics**. If release of contamination has occurred, the user must obtain estimates of various site parameters including:
   a) Depth to water table (feet). Field data measured from the lowest point at which substances are present to the top of the seasonal high water table.
   b) Net precipitation (inches). Taken from existing meteorological data.
   c) Permeability of the unsaturated zone or geologic materials (cm/sec). This factor score is derived from soil descriptions based on particle size distribution (e.g., clay, sand, silt). The method does not specify whether field sampling or existing soil survey information is appropriate but, it is assumed that sampling is preferred.
   d) Physical state of each hazardous substance at the time of disposal obtained from existing records. Categories:
      i. Solid, consolidated or stabilized
      ii. Solid, unconsolidated or unstabilized
      iii. Powder or fine material
      iv. Liquid, sludge, or gas

3. **Containment**. This is a measure of the natural or artificial means that have been used to minimize contaminant migration. For example, liners used for a landfill or diversion structures for a waste lagoon. Data requires field verification.

4. **Waste Characteristics**. The user must evaluate the most hazardous contaminants that could migrate from the site. Contaminants are scored on the following factors:
   a) Toxicity and persistence. Requires knowledge of substances present and may require field data collection and lab analysis. Once substances are identified, the method provides multiple tables with toxicity and persistence rankings for scoring.
   b) Substance quantity. Includes all hazardous substances at the facility excluding contaminated soil and water. Factor scores are based on cubic yards of solid pollutant or drums of liquid pollutant (50 gal) received at the facility. Data must be converted to these units.

5. **Targets**. Defined as follows:
   a) Ground water use within a 3 mile radius of the aquifer. Categories include:
      i. Unusable (e.g., very saline, low yield)
      ii. Commercial, industrial or irrigation
      iii. Drinking water with municipal water from alternate, unthreatened sources available
      iv. Drinking water with no municipal water from alternate, unthreatened sources available
   b) Distance to nearest well.
   c) Population served (i.e., regular users) within a 3 mile radius. The factor score is based on population assuming 3.8 persons per dwelling and 1.5 persons per acre of irrigated land.

METHOD OUTPUT

Figure 11 is a reproduction of the work sheet used to determine ground water sensitivity. The information and index score for a site can be compared to other sites for evaluation. In addition to the ground water migration route work sheet described here, a similar analysis and format is applied to surface water, air routes, fire and explosion potential, and direct contact hazard.

LIMITATIONS OF THE METHOD

1. Hazard does not provide rank sites on an absolute scale. It rather provides a relative comparison of various sites.

2. This system gives the highest rank to the most extensively contaminated, complex and costly sites. Often, remediation monies can be better allocated to cleaning up larger numbers of smaller, less contaminated sites depending upon the nature and extent of the public health hazard.

3. The method is site-specific and cannot be used over large geographic areas.

4. The score is based on the most hazardous substance present. It might be more appropriate to base the score on the entire waste inventory (U.S. Department of Energy, 1987).

5. The direction of hydraulic gradient, a critical factor in contaminant transport, is not considered (U.S. Department of Energy, 1987).

Primary source: Code of Federal Regulations (1989). *Secondary sources:* Caldwell et al. (1981) and Canter et al. (1987).

Ground Water Route Work Sheet					
Rating Factor	Assigned Value (Circle One)	Multi-plier	Score	Max. Score	Ref. (Section)
[1] Observed Release	0 45	1		45	3.1
If observed release is given a score of 45, proceed to line [4]. If observed release is given a score of 0, proceed to line [2].					
[2] Route Characteristics					3.2
Depth to Aquifer of Concern	0 1 2 3	2		6	
Net Precipitation	0 1 2 3	1		3	
Permeability of the Unsaturated Zone	0 1 2 3	1		3	
Physical State	0 1 2 3	1		3	
	Total Route Characteristics Score			15	
[3] Containment	0 1 2 3	1		3	3.3
[4] Waste Characteristics					3.4
Toxicity/Persistence	0 3 6 9 12 15 18	1		18	
Hazardous Waste Quantity	0 1 2 3 4 5 6 7 8	1		8	
	Total Waste Characteristics Score			26	
[5] Targets					3.5
Ground Water Use	0 1 2 3	3		9	
Distance to Nearest Well/Population Served	0 4 6 8 10 12 16 18 20 24 30 32 35 40	1		40	
	Total Targets Score			49	
[6] If line [1] is 45, multiply [1] x [4] x [5] If line [1] is 0, multiply [2] x [3] x [4] x [5]				57,330	
[7] Divide line [6] by 57,330 and multiply by 100	S_{gw} =				

Figure 11. Hazard Ranking System Ground Water Routing Work Sheet

Source: Code of Federal Regulations (1989)

2.4.2 MICHIGAN SITE ASSESSMENT SYSTEM

GENERAL PURPOSE

The Michigan Site Assessment System (SAS) is a modified version of the EPA Hazard Ranking System. The Michigan system, however, puts more emphasis on human population exposure and includes a more detailed evaluation of chemical hazards. It is designed to rank existing hazardous waste facilities for remedial action and has been used in ranking sites for Superfund cleanup.

Similar to Hazard, the SAS addresses a wide variety of contaminant pathways. It produces relative index scores for: 1) potential harm to humans resulting from substance migration via surface water, ground water and air routes, 2) potential harm from explosions and fire, and 3) potential harm from direct human contact. For the purposes of this paper, only the ground water sensitivity index will be reviewed.

SCALE

This method is designed for use on individual sites.

METHOD OVERVIEW AND DATA REQUIREMENTS

The ground water section of SAS requires considerable information about the facility, its surroundings, hazardous substances present, and hydrogeology of the area. Because of the detailed analysis, considerable professional expertise is required. The following describes how the analysis is performed.

1. **Estimating release potential of substance.** The user must first evaluate release potential of contaminants based on the physical state of chemicals present and the effectiveness of containment structures to minimize or prevent chemical release. All containment structures must be:
   a) Identified on a map
   b) Rated as adequate, unknown, or inadequate in terms of containment effectiveness. Evaluation is a subjective judgement based on whether the facility was "designed, constructed, and is operating so that emissions of chemicals are effectively prevented from entering the environment."
   c) Rated for physical state of chemicals (solid, semi-solid, liquid or gas) in every containment structure that was determined less than adequate in (b) above.
   d) Rated for waste quantity (kg) in each structure.
   e) Rated for percent waste (%) on the site that is within the containment structures.
   f) Factor scores in (a) through (e) above are combined through arithmetic equations into a score of 0, 1 or 2. Sites with release potentials of 0 are not considered in the rest of the analysis.

2. **Environmental exposure**: evaluates site attributes and surroundings in terms of waste release and movement. Factors include earth material and thickness of unsaturated zone adapted from the EPA Surface Impoundment Assessment Methodology (Silka and Swearingen, 1978):
   a) Earth Materials
      i. Unconsolidated Rock -- particle size classification
         a. Gravel, coarse to medium sand.
         b. Fine to very fine sand.
         c. Sand with < 15% clay or silt.
         d. Sand with > 15% but < 50% clay.
         e. Clay with < 50% sand.
         f. Clay > 15 feet continuous.

ii. Consolidated Rock -- structural information
   a. Cavernous or fractured limestone, evaporites, basalt lava, fault zones.
   b. Fractured igneous and metamorphic rock, poorly cemented sandstone.
   c. Moderately cemented sandstone, fractured shale.
   d. Well-cemented sandstone.
   e. Siltstone.
   f. Shale.

iii. Permeability (cm/sec) -- representative ranges are provided for earth materials.

b) Thickness of the unsaturated zone (feet) based on the seasonal high water table.

3. **Targets**
   a) Rate target populations. Defined as number of homes within 1/2 mile of the site in the direction of ground water flow.
   b) Rate ground water resource value. Accomplished by rating earth materials and thickness of the saturated zone. Criteria is identical to 2(a) and 2(b) above except that the rating scale is different and applied to saturated zone. Scales were adapted from the EPA Surface Impoundment Assessment Methodology (See *Section 1.3.1*).

4. **Rate existing exposure** in terms of number of people actually exposed to the chemical (documented). Rating is based on the difference between documented exposure level and background exposure level (parts per billion).

5. **Rate chemical hazard** in terms of four criteria: toxicity, bioaccumulation, persistence, and reactivity[1] as follows:
   a) Toxicity
      i. Mammalian -- oral, dermal and inhalation LD50 (mg/kg).
      ii. Genotoxicity [ratings based on data from the International Agency for Research on Cancer (IARC), the National Cancer Institute (NCI), or the National Toxicity Program (NTP)].
      iii. Subchronic/chronic toxicity (mg/kg).
      iv. Ecological toxicity.
         a. 96 hr. LC_{50} in fish (mg/l).
         b. EC_{50} chronic for aquatic life (mg/l).
         c. LD_{50} in Avian species (mg/l).
         d. Mean Inhibitory Limit (ILM) in terrestrial plants (mg/l).
   b) Bioaccumulation (fish bioconcentration factor or log K_{ow}).
   c) Persistence (half-life in months).
   d) Detailed waste quantity estimates (kg) must be included to complete the chemical hazard rating.

METHOD OUTPUT

The SAS produces a site index that can be compared to other site indices for evaluation. In addition to the ground water route described here, a similar analysis and format is applied to surface water, air routes, fire/explosion potential, and direct contact hazard.

[1]Because this review addresses only the ground water pollution potential, flammability and reactivity criteria are not included.

LIMITATIONS OF THE METHOD

1. The SAS does not provide an absolute scale for hazard. It only provides a relative comparison of various sites.

2. This system gives the highest rank to the most extensively contaminated, complex and costly sites. Often, remediation monies can be better allocated to cleaning up larger numbers of smaller, less contaminated sites depending upon the nature and extent of the public health hazard.

3. The method is site-specific and is not appropriate for large geographic areas.

Primary source: Michigan Department of Natural Resources (1983). *Secondary sources:* Code of Federal Regulations (1989), Silka and Swearingen (1978), and Trojan (1986).

SECTION 3: LARGE SCALE SENSITIVITY RANKING

The methods included in this section typically produce index scores of hydrogeologically sensitive areas which can be used to construct sensitivity maps. EPA DRASTIC is perhaps the most well-known although several others have been developed. They are typically easy to use and rely on existing information such as maps, soil surveys, and government documents. Field data collection is not usually required. Consequently, resolution is low and scale is not appropriate for site-specific evaluation. These methods are ideal for computerized applications such as Geographic Information Systems (GIS).

Methodologies reviewed in this section are used primarily by government agencies for policy development, planning, regulation and management, program implementation, and education. They can often be used by county commissioners, planners and other individuals with limited hydrogeologic expertise. Exceptions include portions of the Minnesota Sensitivity Rating Method and the Trojan/Perry Method. The methodologies can be organized as follows:

1. Methods that evaluate hydrogeologic sensitivity only
   a) DRASTIC
   b) Minnesota Ground Water Sensitivity Map
   c) Minnesota Sensitivity Rating Method
   d) Wisconsin Ground Water Sensitivity Map
   e) Illinois Ground Water Contamination Potential Rating System

2. Methods that evaluate hydrogeologic sensitivity and contaminant behavior
   a) Trojan/Perry Method

Most large-scale techniques evaluate only hydrogeologic sensitivity. The Trojan/Perry Method, however, incorporates contaminant behavior and properties.

3.1 HYDROGEOLOGIC SENSITIVITY ONLY

3.1.1 DRASTIC

GENERAL PURPOSE

DRASTIC is a widely used ground water vulnerability rating system developed by the US EPA. It "allows the pollution potential of any area to be systematically evaluated anywhere in the United States" (Aller et al., 1986). It is a tool to aid planners, managers and other decision makers in preliminary assessment of ground water vulnerability using existing data in the form of maps, soil surveys and hydrogeologic information.

SCALE

Since DRASTIC uses existing data, the scale is limited primarily by map scale and the resolution of existing information. DRASTIC is usually not useful on areas smaller than 40 acres.

METHOD OVERVIEW

Development of a DRASTIC index requires information on 7 hydrogeological parameters: depth to water, net recharge, aquifer media, soil media, topography (slope), vadose zone materials and hydraulic conductivity. Information is gathered from existing sources including soil atlases, geologic and topographic maps. Field sampling is not required.

Hydrologic factors are evaluated in the context of two land use settings: agricultural and non-agricultural. The additional pollution risk associated with agriculture is incorporated into the index by means of factor weights (multipliers) as described below.

Information on the 7 factors can be used either of two ways in the DRASTIC system:

1. **Independent development of an index.** DRASTIC indices for different areas can be developed from data on the 7 factors. Values and weights for factors are provided in the user's manual as shown in Table 7. The index is determined from factor values using simple arithmetic as outlined in the DRASTIC manual (Aller et al., 1985). Note that weights are given for both agricultural and non-agricultural settings.

Table 7. Sample rating chart for DRASTIC including factor values and weights.

Beaches, Beach Ridges and Sand Dunes -- General				
Feature	Range	Weight	Rating	Number
Depth to Water Table	0-5	5	10	50
Net Recharge	10+	4	9	36
Aquifer Media	Sand & Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	0-2%	1	10	10
Impact Vadose Zone	Sand & Gravel	5	8	40
Hydraulic Conductivity	1000-2000	3	8	24
			DRASTIC Index	202

Beaches, Beach Ridges and Sand Dunes-Agricultural				
Feature	Range	Weight	Rating	Number
Depth to Water Table	0-5	5	10	50
Net Recharge	10+	4	9	36
Aquifer Media	Sand & Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	0-2%	3	10	30
Impact Vadose Zone	Sand & Gravel	4	8	24
Hydraulic Conductivity	1000-2000	2	8	16
			Agricultural DRASTIC Index	225

Source: Aller et al. (1985)

2. **The "cookbook" method.** The DRASTIC manual also includes descriptions of major geologic settings throughout the United States. Predetermined indices are provided for each geologic setting along with pre-assigned weights for both agricultural and non-agricultural land use settings. An example for a geologic setting consisting of "beaches, ridges and sand dunes" is shown in Figure 12.

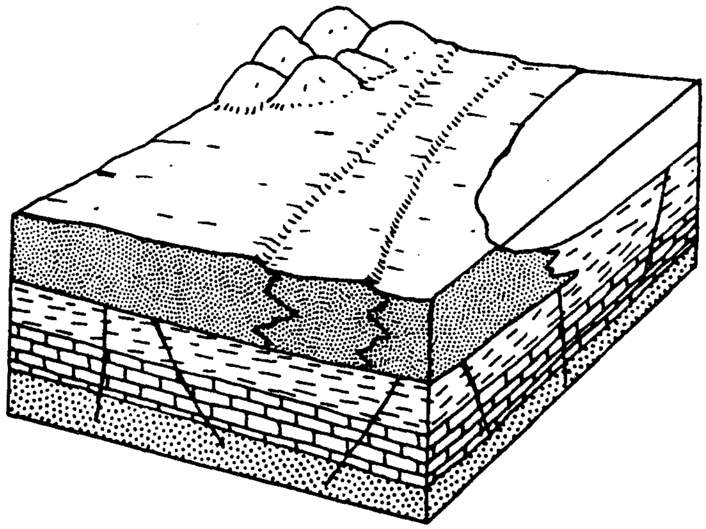


Figure 12. Typical Geologic Setting from DRASTIC: Beaches, Beach Ridges and Sand Dunes
Source: Aller et al. (1985)

To use the cookbook method, the user first locates a description in the DRASTIC manual that most closely matches the geological setting to be analyzed. The user then compares ranges of DRASTIC's predetermined parameters with actual data. In our example, depth to water data from well logs would be compared to the range of values for depth to water given in Table 8. If the actual data fall within the range specified by the DRASTIC manual, the predetermined index score is used. If actual data are not within the range specified, the user makes appropriate changes to the factor scores and the predetermined DRASTIC index is modified.

Table 8. DRASTIC Index Typified for a Geologic Setting

Depth to Water (feet)	
Range	Rating
0-5	10
5-15	9
15-30	7
30-50	5
50-75	3
75-100	2
100+	1
Weight: 5	Agricultural Weight: 5

Source: Aller et al. (1985)

METHOD OUTPUT

DRASTIC produces an index score for a geographic area which can be compared to index scores from other geographic areas. The size of the geographic area is determined by map scale. The information can also be digitized to produce sensitivity maps similar to those produced by the Minnesota and Wisconsin ground water rating systems.

DATA REQUIREMENTS

The DRASTIC methodology has two major portions: 1) designation of hydrogeologic units, and 2) a relative ranking based on hydrogeologic parameters. Information needed is outlined below.

I. Depth to the water table (feet).

II. Net recharge (inches) -- amount of water per unit land area which penetrates the ground surface and reaches the water table.

III. Aquifer media -- characteristics used to estimate impact of the aquifer medium on ground water movement.
   A. Massive shale
   B. Metamorphic/igneous
   C. Weathered metamorphic/igneous
   D. Thin bedded sandstone, limestone, shale sequences
   E. Massive sandstone
   F. Massive limestone
   G. Sand and gravel
   H. Basalt
   I. Karst limestone

IV. Soil media -- characteristics used to estimate impact of the upper weathered zone of earth (depth 6 feet or less) on ground water movement.
   A. Thin or absent
   B. Gravel
   C. Sand
   D. Peat
   E. Shrinking and/or aggregated clay
   F. Sandy loam
   G. Loam
   H. Silty loam
   I. Clay loam
   J. Muck
   K. Non-shrinking or aggregated clay

V. Topography -- land slope (%).
   A. 0-2
   B. 2-6
   C. 6-12
   D. 12-18
   E. 18+

VI. Vadose zone media -- characteristics used to estimate impact of vadose zone materials on attenuation and neutralization of contaminants.

A. Silt/clay
B. Shale
C. Limestone
D. Bedded limestone, sandstone, shale
E. Sand and gravel with significant silt and clay
F. Metamorphic/igneous
G. Sand and gravel
H. Basalt
I. Karst limestone

VII. Hydraulic conductivity (gallons per day/foot).

METHOD OUTPUT

DRASTIC produces an index score for an area that can be compared to index scores from other areas.

LIMITATIONS OF THE METHOD

1. DRASTIC only provides a relative ranking among sites, it does not provide an absolute scale of potential site hazard.

2. Waste characteristics are not considered. DRASTIC does not evaluate vulnerability of ground water to specific contaminants.

3. Health and other effects on users are not considered.

4. DRASTIC was developed in heterogeneous areas throughout the United States. It has been reported that it does not have good resolution in uniform geological settings (Higher, 1986).

Primary source: Aller et al. (1985). *Secondary sources:* Aller et al. (1986), Canter et al. (1987), Curry (1987), Trojan (1986).

3.1.2 MINNESOTA GROUND WATER SENSITIVITY MAP

GENERAL PURPOSE

In 1989, Minnesota used a modified form of DRASTIC to produce a state-wide map of ground water sensitivity. The map is used to help focus state efforts in five specific areas related to ground water pollution including: regulation, monitoring, planning, prevention, and public information efforts. It is a planning and educational tool for general applications.

SCALE

The scale in this method is map dependent. In the Minnesota survey, map scales ranged from 1:250,000 to 1:1,000,000.

METHOD OVERVIEW

This method assesses relative ground water susceptibility to contamination using previously published and compiled data. The process can be broken down into 3 general phases:

1. Data collection
2. Data digitization
3. Map generation

Since the method was designed for use over large areas, much of the data collection phase involves obtaining appropriate geologic maps. These maps were digitized for use in computerized overlay techniques. From the digitized data, a ground water sensitivity map was generated.

To produce a sensitivity map, the user must first obtain geologic and hydrogeologic maps containing information on four factors:

1. Aquifer materials
2. Vadose zone materials
3. Net recharge
4. Soil type

A sensitivity map is developed as follows:

1. **Aquifer materials.** Thematic maps containing information on lithostratigraphy, hydrogeology and bedrock hydrogeology are digitized and used to estimate aquifer materials present. Additional inventories of buried drift wells may also be necessary in areas where localized water-bearing formations are too small to be classified as regional aquifers (i.e., beyond resolution capabilities of large-scale geologic maps). Factor scores can then be generated based on this information.

2. **Estimate recharge potential.** Estimates in the Minnesota survey were derived from hydrological soil groupings of the Minnesota Soil Atlas Series and used to develop factor scores.

3. **Identify soil materials.** In the Minnesota survey, textural classifications derived from the Minnesota Soil Atlas were used to develop factor scores.

4. **Identify vadose zone materials.** Because soil maps only give estimates to the bottom of the root zone, the materials which occupy the zone between the soil and the bedrock must also be estimated.

METHOD OUTPUT

The digitized information can be used to generate individual component maps as shown in Figures 13-16. These computerized component maps are overlaid to produce a general ground water sensitivity map similar to Figure 17.

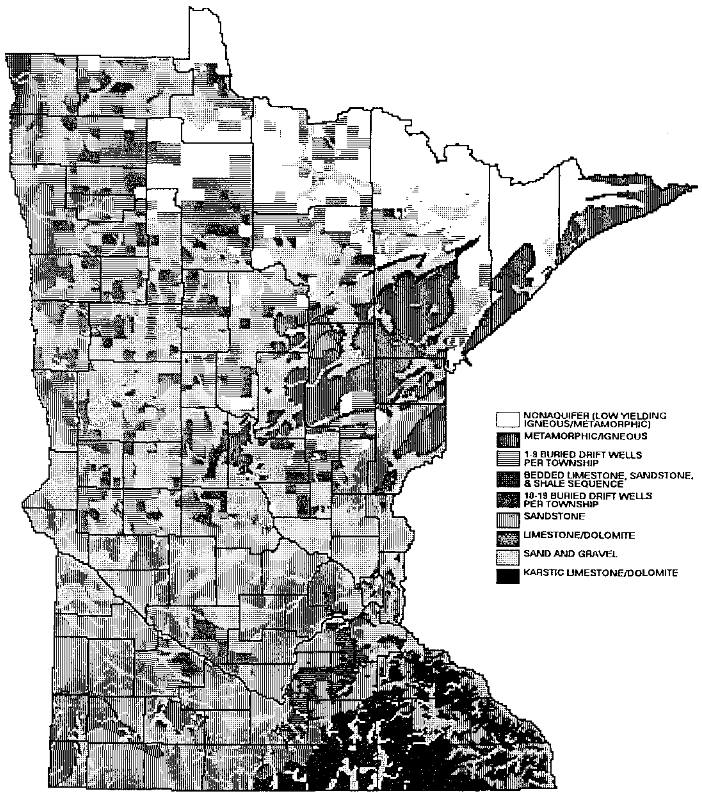


Figure 13. Minnesota Aquifer Materials Map
Source: Porcher (1989)

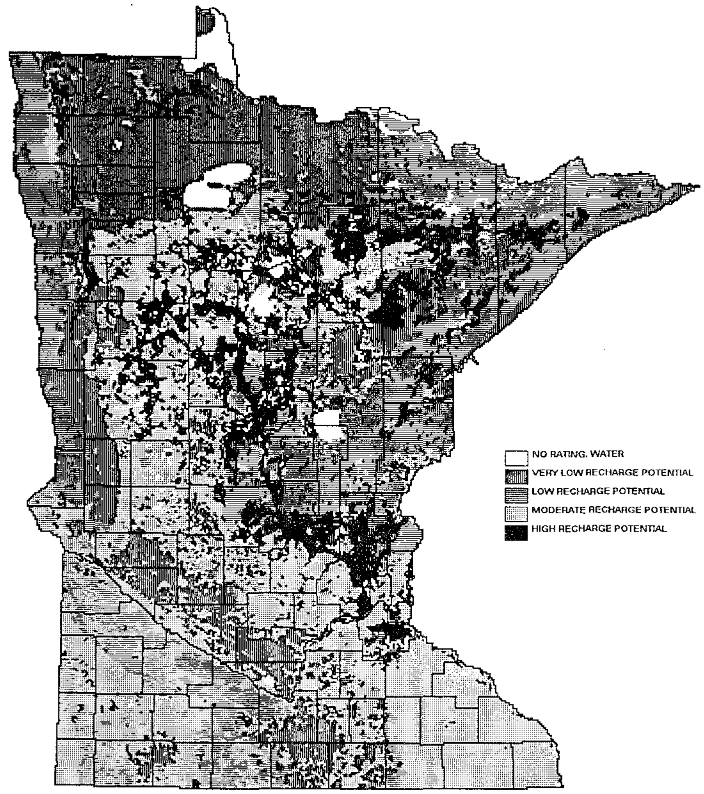


Figure 14. Minnesota Recharge Potential Map
Source: Porcher (1989)

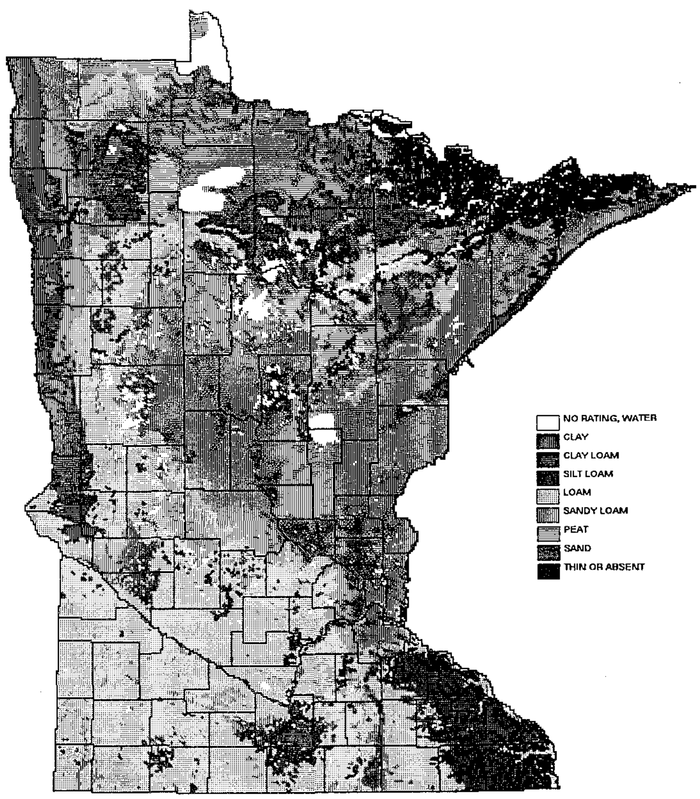


Figure 15. Minnesota Soil Materials Map
Source: Porcher (1989)

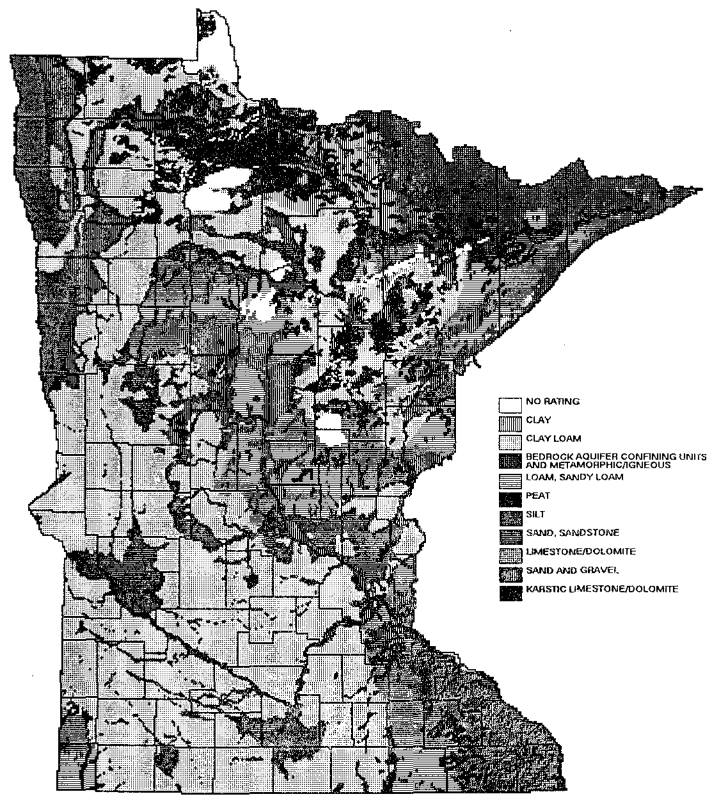


Figure 16. Minnesota Vadose Zone Materials Map
Source: Porcher (1989)

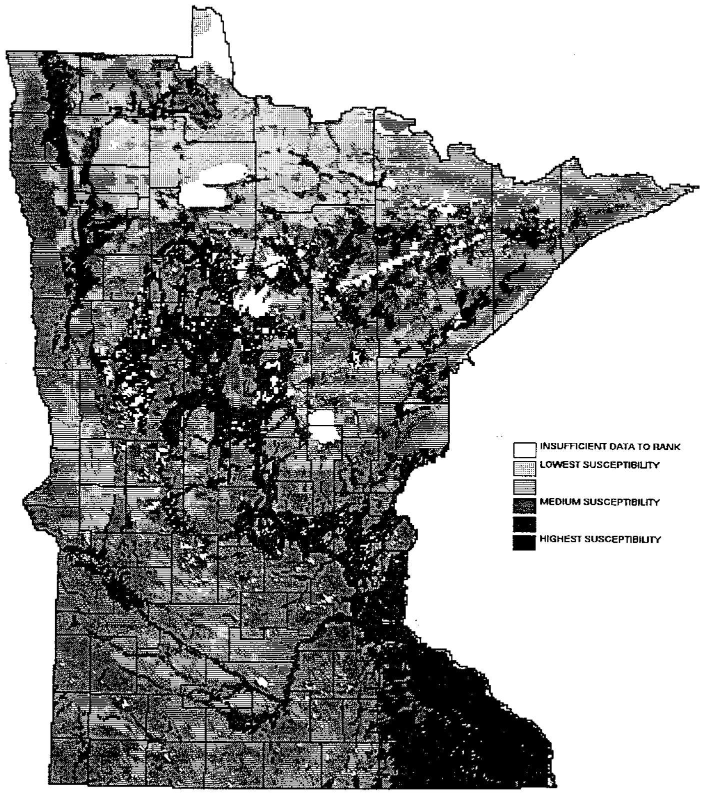


Figure 17. Minnesota Ground Water Sensitivity Map
Source: Porcher (1989)

DATA REQUIREMENTS

1. **Aquifer materials**. Estimated from geologic maps and well logs. Specific information required includes:
   a) Aquifer composition
      i. Metamorphic/igneous
      ii. Bedded limestone, sandstone and shale sequences
      iii. Sandstone
      iv. Limestone/dolomite
      v. Sand and gravel
      vi. Karstic limestone
   b) Number of buried drift wells per township in areas too small to be classified as aquifers.

2. **Recharge potential**. Estimated as being directly proportional to the infiltration rate of hydrologic soil groups defined by the Minnesota Soil Atlas Series. Ratings, which range between 0 and 9, are subjective estimates made by the user.

3. **Soil materials**. Estimated from the Minnesota Soil Atlas.

4. **Vadose zone materials**. Estimated from existing geologic maps.

LIMITATIONS OF THE METHOD

1. Limitations that apply to DRASTIC also apply to this methodology.

2. A primary limitation of this method is related to scale. Most information was taken from maps published at a scale of approximately 1:500,000 (1" = 8 miles). Consequently, it is useful only on a broad, regional level. Extrapolation to more localized levels for purposes of landfill siting and other activities requiring high resolution information is not appropriate.

3. A third limitation involves the use of maps and soil survey information to estimate hydrologic parameters. While these sources provide general information, they are not as accurate as field data and do not often represent spatial variability accurately. For example, properties such as hydraulic conductivity can vary by several orders of magnitude at the scale employed by this method.

4. The method only considers geologic sensitivity. Specific contaminant properties and behavior are not considered. The sensitivity estimate is based on the assumption that the contaminant moves at the same rate as the average velocity of the ground water. This is not the case for most organic compounds.

5. Soil organic matter, an important factor in organic waste attenuation, is not specifically incorporated into the index.

Primary source: Porcher (1989).

3.1.3 MINNESOTA SENSITIVITY RATING METHOD

GENERAL PURPOSE

The Minnesota Sensitivity Rating Method estimates hydrogeologic sensitivity by assessing vertical permeability of geologic materials between the land surface and underlying aquifer. Evaluation procedures for deep aquifers are also included. Sensitivity estimates are based on estimated travel time from the soil surface to the aquifer.

The methodology was designed to assist state/local governments, industries, businesses, and individual citizens in evaluating land use impacts on ground water resources. Four broad activities categories are listed: planning, regulation-management, related program implementation, and education. Example applications include preliminary screening of public facilities, waste disposal sites, zoning evaluation, land use permitting-regulation, and sanitary code improvements.

SCALE

The scale is variable. Level 1 assessment is usually done at the soil survey map scale (1:15,840 or 1:24,000). Smaller scale county maps can also be used (1:100,000), if necessary.

METHOD OVERVIEW AND DATA REQUIREMENTS

This methodology is developed in three levels of analysis. Each succeeding level builds on the previous level by incorporating additional information. Accuracy and sophistication of analysis also increase at each level.

Level 1 assessment is based on estimates of vertical permeability of the soil column and estimated seasonal high water table depth.

Level 2 assessment is based on estimates of vertical permeability of vadose zone material between the lowest soil horizon and the water table.

Level 3 assesses potential for deep aquifer contamination.

A Level 1 assessment can be conducted with minimal training in hydrogeology, but Level 2 and 3 assessments should be conducted only by a trained hydrogeologist. The following is an overview of each level and information required.

Level 1: Surface analysis based on soil survey information.

Estimates permeability of the soil profile within five feet of the ground surface from county soil survey maps. Users must:

1. Become familiar with the county soil survey, particularly nomenclature and terminology.
2. Identify parent material for each soil series within the county.
3. Identify texture of the lowest described horizon for each soil series (e.g. sand, loamy sand, sandy loam, loam).
4. Identify depth to the seasonal high water table for each mapping unit on the soil survey.
5. Create a table by grouping all soil series according to parent material.
6. Prepare a parent materials map by color coding soil series on a county soil map according to parent material.
7. Prepare a sensitivity map by color coding map units according to sensitivity ratings provided in the methodology (see Table 9).

Level 2: Assessment of vadose zone materials.

Level 2 assesses the permeability of materials between the soil profile and water table. Analysis requires detailed professional geologic analysis. Either of two methods can be used as follows:

Point Method:

1. Collect all available point hydrogeologic data (e.g., driller and engineering logs). References and sources are provided.
2. Organize data in the work sheet format provided in the manual.
3. Determine vadose zone thickness at each data point location. Procedure requires accurate estimates of water table depth.
4. Interpret terminology used in driller and engineering logs. Nomenclature can be ambiguous and confusing.
5. Determine presence of low or moderate permeability units according to guidelines provided in manual.
6. Determine geologic material present at the water table according to guidelines provided in the manual.
7. Rate each data point according to guidelines as shown in Table 10.
8. Plot data points and ratings on a map.

Table 9. Level 1 Sensitivity Ratings for the Minnesota Sensitivity Rating Method

Geologic Material	Sensitivity Rating	
Unconsolidated Deposits		
	Depth to Water Table	
	<6 feet	>6 feet
Outwash, glacial lake sand & gravel	Very High	Very High
Terrace sand & gravel deposits	Very High	Very High
Organic material, peat	High	Moderate
Loess, glacial lake and terrace silt & fine sand	High	High
Sandy loam till, loamy sand till	High	Moderate
Alluvium, colluvium	High	Moderate
Loamy till, clay loam till, clay till	Moderate	Low
Glacial lake clay & silty clay	Moderate	Low
Bedrock or Bedrock Residiuum		
Limestone, dolomite	Very High	Very High
Sandstone	Very High	High
Igneous & metamorphic rocks	High	High
Siltstone	Moderate	Moderate
Shale	Low	Low

Source: Minnesota Department of Natural Resources (1991)

Area Method:

1. Construct or obtain a surficial geology map. Complete geological investigation is recommended, but existing maps may be used if detail is adequate.
2. Construct or obtain a depth to water table map with three ranges: less than 10 feet, between 10 and 20 feet, greater than 20 feet.
3. Determine presence and persistence of mapped units. For example, existing surficial deposit maps may represent only a thin veneer over more persistent underlying map units. Such units must be identified for accurate sensitivity assessment.
4. Construct a sensitivity map by overlaying the water table map with the surficial geologic map. Sensitivity ratings are determined according to guidelines provided in the methodology.

Level 3: Evaluation of deep aquifer sensitivity

This assessment rates deep aquifer sensitivity based on cumulative thickness of confining layers (not just occurrence as determined in Level 2). Deep aquifers are defined by the existence of one or more 10-foot thick confining layers in the geologic profile. Confining layers are described in geologic nomenclature.

Sensitivity is estimated as a function of how well a deep aquifer is protected by confining layers. The presence of one very thick confining layer or multiple thin confining layers provide protection. Since deep aquifers are not usually prone to land use impacts, ratings are designated as "low" or "very low." Rating guidelines for this level are shown in Table 11. An "L" score between 1 and 5 constitutes a low rating, while "L" of less than 5 is rated very low. As indicated, a combined confining layer thickness of 50 feet is required for a "very low" rating.

Table 10. Level 2 Sensitivity Ratings for the Minnesota Sensitivity Rating Method

	Water Table Material Rating								
	Karstic Conditions 1			2		3		4	
Total vadose zone thickness (feet)	<20	20-50	>50	<20	>20	<20	>20	<20	>20
LOW AND MODERATE PERMEABILITY UNITS IN THE VADOSE ZONE									
No low or moderate permeability units	VH	VH	H	VH	H	M	M	L	L
Aggregate of thin low permeability units >10 feet thick		H	M		M		M		L
Single moderate permeability unit >20 feet thick		H	M		M		M		L
At least one low permeability unit >10 feet thick		M	L		L		L		L

VH = Very High H = High M = Moderate L = Low

Source: Minnesota Department of Natural Resources (1991)

METHOD OUTPUT

This method produces a geologic sensitivity map for each level of analysis.

LIMITATIONS OF THE METHOD

1. Does not consider land use impacts.

2. Health and other effects on users is not considered.

3. Maps and soil survey information are limited in their ability to estimate hydrologic parameters. These sources provide general information, but are not as accurate as field data. Properties such as hydraulic conductivity, for example, can vary by several orders of magnitude at the scale employed by this method.

4. The method only considers geologic sensitivity. Specific contaminant properties and behavior are not considered. Sensitivity estimates are based on the assumption that contaminants move at the average velocity of ground water. This method would underestimate travel time (overestimate sensitivity) for organic compounds if adsorption and attenuation were occurring.

Table 11. Calculation of "L" for deep aquifers--Minnesota Sensitivity Rating Method.

Step 1.	$\frac{\text{Thickness of each confining layer}}{10}$ = approximate "L" value
Step 2.	Round approximate "L" value down to next whole number to get the confining layer "L" score.
Step 3.	Add the "L" scores of each confining layer to get total score for aquifer. If the score is L-5 or greater, the sensitivity rating is "Very Low."

Example 1. A single confining layer 69 feet thick.

Step 1.	$\frac{\text{69 feet}}{10}$ = L-6.9
Step 2.	L-6.9 rounded down = L-6
Step 3.	Deeper aquifer is rated "Very Low" because confining layer score is greater than L-5.

Example 2. Three confining layers 15, 11, and 23 feet thick.

Step 1.	$\frac{\text{15 feet}}{10}$ = L-1.5	$\frac{\text{11 feet}}{10}$ = L-1.1	$\frac{\text{23 feet}}{10}$ = L-2.3
Step 2.	L-1.5 rounded down = L-1 L-1.1 rounded down = L-1 L-2.3 rounded down = L-2		
Step 3.	Adding layer "L" scores gives a total score of L-4. The deeper aquifer is rated "Low" because the total confining layer score is less than L-5.		

Source: Minnesota Department of Natural Resources (1991)

Primary source: Minnesota Department of Natural Resources (1991).

3.1.4 WISCONSIN GROUND WATER SENSITIVITY MAP

GENERAL PURPOSE

The Wisconsin Ground Water Sensitivity Map was developed as part of a comprehensive plan to manage Wisconsin's water resources. The portion of the plan which contains the assessment methodology was designed to facilitate decision making in state agencies by helping to identify areas prone to contamination. Specific goals and objectives of the project include:

1. Develop a statewide assessment of ground water quality and quantity including historical and geographic trends.
2. Identify and assess significant ground water contaminants, contamination sources, and past contamination incidents in Wisconsin.
3. Evaluate physical resource information relating to the state's ground water (e.g., soils, geology and water table depth).
4. Identify areas of the state where ground water management activities should be focused.

This method is useful over large areas where general information about geologic sensitivity is needed. It can also be used for ranking management activities related to ground water based on contamination susceptibility. Finally, the susceptibility map is useful for informational and educational purposes.

SCALE

The scale for this method is statewide or regional.

METHOD OVERVIEW

Five geologic and soil factors are evaluated: 1) soil permeability and texture, 2) surficial deposits, 3) depth to bedrock, 4) bedrock type, and 5) depth to water table.

In order to evaluate these factors, an interdisciplinary team of specialists chose a set of appropriate maps that accurately represented these factors within the state of Wisconsin. The most common map scale used was 1:250,000. The maps were digitized and overlaid to get point estimates of the combined factors. Once the maps were overlaid, the numerical indices for each point on the map were calculated. The final index scores estimating relative ground water sensitivity between areas were plotted on a state map (no example was included in Schmidt, 1987).

To use this methodology, a user would have to:

1. Digitize soil data from an appropriate map. Schmidt (1987) used the *Soil Association of Wisconsin--1986* at a scale of 1:250,000.

2. Digitize surficial deposit information derived from quaternary geology maps. Schmidt (1987) used Wisconsin quaternary geology maps at a scale of 1:500,000.

3. Digitize a map that estimates the depth to water table. Schmidt (1987) used a map compiled by the USGS at a scale of 1:250,000. The author noted that this was the most difficult factor to map on a statewide basis [see (4) in *Limitations of the Method*].

4. Digitize a map that estimates the type of bedrock. Schmidt (1987) used the *Bedrock Geology of Wisconsin--1981* published at a scale of 1:500,000.

5. Digitize a map estimating the depth to bedrock. Schmidt (1987) used the *Depth to Bedrock Map--1973* published by the USGS at a scale of 1:1,000,000.

Digitized maps identified in 1-5 above are then overlaid by computer. A rating scheme shown in Table 12 is applied to pixels on the overlaid maps which gives a numerical sensitivity rating for each point. Because hundreds or thousands of sensitivity values are generated by the computer on a small-scale map, they must be grouped into categories such as "high," "medium," "low" or other appropriate classification. Schmidt (1987) used 20 different sensitivity categories for Wisconsin. Based on pixel values and the chosen sensitivity categories, the computer generates a ground water sensitivity map.

METHOD OUTPUT

The method produces index scores for different map units or geographical areas.

DATA REQUIREMENTS

All data used in this method are derived from maps that either 1) include the following information, or 2) include information from which the factors listed below can be derived.

1. Qualitative description of bedrock:
   a) Carbonates
   b) Sandstone
   c) Igneous, metamorphic, volcanic
   d) Shale
2. Depth to water table (3 ranges):
   a) 0-20 ft.
   b) 20-50 ft.
   c) > 50 ft.
3. Qualitative description of soil characteristics (4 ranges):
   a) Very coarse texture and very high permeability
   b) Medium/coarse texture and medium/high permeability
   c) Medium texture and medium permeability
   d) Fine texture and low permeability
4. Qualitative description of surficial deposits (5 classifications):
   a) Sand and gravel
   b) Sand
   c) Loam
   d) Clay
   e) Peat

LIMITATIONS OF THE METHOD

1. The method was not designed for site-specific investigations. Only 5 factors are used in the analysis. In addition, specific values for most of the factors are derived from maps. This type of information is only as accurate as information incorporated into the maps, and only as precise as the scale of the map allows. For example, most of the maps for Wisconsin were compiled at the 1:250,000 scale. Such resolution is not precise enough for investigations at a larger map scale.

Table 12. Rating Scheme for the Wisconsin Ground Water Sensitivity Map

		Final Rating Scheme		
Multiplier Values:	Type of Bedrock Multiplier	Surficial Deposits Multiplier	Soil Characteristics Multiplier	Water Table Multiplier
If Depth to Bedrock:				
0-5' (70% of Area)	13	0	1	1
0-5' (35% - 70% of Area)	11	1	2	1
5'-50'	6	4	3	3
50'-100'	0	8	4	3
>100'	0	8	4	3

Rating Scheme Value:

Resource Map	Attribute	Value
Type of Bedrock	Carbonate	1
	Sandstone	5
	Ign./metamorphic	6
	Shale	10
Depth to Water Table	0-20'	1
	20'-50'	5
	>50'	10
Soil Characteristics	Coarse texture/high permeability	1
	Medium coarse texture/high-medium permeability	3
	Medium texture/medium permeability	6
	Fine texture/low permeability	10
Surficial Deposits	No materials	0
	Sand and gravel	1
	Sandy	2
	Peat	5
	Loamy	6
	Clayey	10

Formula for Composite Score:
[Bedrock Type(value) x Bedrock Type(multiplier)] + [Surficial Deposits(value) x Surficial Deposits(multiplier)] + [Depth to Water Table(value) x Depth to Water Table (multiplier)] + [Soil Characteristics(value) x Soil Characteristics(multiplier)] = Composite Score

Source: Schmidt (1987)

2. This method estimates hydrogeologic vulnerability only.

3. This method is useful on uncontaminated sites only. Waste characteristics and effects on users are not considered. No consideration is given to properties or behavior of specific contaminants.

4. Accurate water table information is often difficult to obtain. Data were scarce in Wisconsin. Topography was more variable than map resolution could accurately represent, and water tables fluctuate seasonally and annually. Consequently, depth to water table is considered the least reliable information of the maps used.

5. Soil organic matter, an extremely important factor in organic waste attenuation, is not specifically incorporated into the method.

Primary source: Schmidt (1987). *Secondary source:* Trojan (1986).

3.1.5 ILLINOIS GROUND WATER CONTAMINATION POTENTIAL RATING SYSTEM

GENERAL PURPOSE

The Illinois methodology provides a preliminary appraisal of ground water sensitivity on a regional scale. According to the manual, it is useful for preliminary screening of areas for new waste disposal sites or evaluating the suitability of existing waste disposal operations. It is designed to estimate hydrogeologic sensitivity only.

SCALE

The scale for this method is regional.

METHOD OVERVIEW AND DATA REQUIREMENTS

The Illinois methodology requires construction of a contamination-potential map from existing data sources. The map shows how earth materials are distributed both horizontally across the land surface and vertically in "stacked" units below the surface. This combination identifies relationships among geological units which can be used to estimate sensitivity.

Geological stack unit maps are prepared to predetermined depths depending on intended use. A depth of 20 feet is used for screening surface and near surface waste disposal sites (e.g., septic systems, surface spread sludge disposal). A depth of 50 feet is used for screening municipal land burial waste sites.

Map preparation requires the following steps:

Step 1. Create a topographic/soil base map by overlaying a USGS topographic map (1:24,000 or 1:62,500) onto a USDA soil map. The resulting map is a functional surficial geology map.

Step 2. Determine drift thickness and thickness of stratigraphic units underlying the topographic/soil base map using information from geologic reports, maps, field observations, well-logs, core samples, and test-drillings.

Step 3. Cross-sectional diagrams can be constructed to help identify continuity of sub-surface units.

Step 4. Based on the above information, a stack unit map can be constructed to either 20 or 50 feet.

Step 5. The stack unit map developed in Step 4 is transformed into a Contamination-Potential map by combining stack units and vertical sequences into sets of geological units. Pre-rated designations (A1, A2, etc.) are assigned to observed geologic sequences by comparing mapped sequences to descriptive sequences provided in the user's manual as shown in Figure 18.

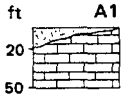
DESCRIPTIONS AND RATINGS OF GEOLOGIC SEQUENCES
Plate 1: Potential for Contamination of Shallow Aquifers by Land Burial of Municipal Wastes

Sequences, Ratings, and Descriptions

A — modern river deposits, thick glacial sand and gravel or permeable bedrock at or within 20 feet of the surface.

Geologic limitations. The potential for contaminating shallow aquifers is high. These materials are only suitable for land burial of *non*contaminating wastes.

A1



— permeable sandstone, dolomite, or limestone lying at or within 20 feet of land surface throughout these areas. Bedrock is primarily Ordovician, Silurian, and Mississippian; Pennsylvanian bedrock is described elsewhere.

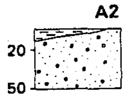
Significant groundwater supplies may be obtained from these materials. Porous sandstone and fracture and joint systems in limestone and dolomite allow water and contaminants to move rapidly into shallow wells finished in these materials. Up to 20 feet of till, loess, or lacustrine materials may overlie the bedrock, but provide little protection from leachates of wastes buried in trenches, which are commonly 20 feet deep. Hydraulic conductivity in sandstone and fractured rock is usually more than 1×10^{-4} cm/sec.

This map sequence occurs mostly in the driftless and thin-drift areas of northern and southern Illinois as well as on the slopes adjacent to the Mississippi and lower Illinois Rivers.

Geologic limitations. The potential for contaminating shallow aquifers is high. Land burial should be restricted to *non*contaminating wastes.

Principal counties. Alexander, Carroll, Greene, Hardin, Jersey, Jo Daviess, Johnson, Kankakee, Monroe, Ogle, Pike, Pope, Scott, Stephenson, Union, Whiteside, and Winnebago.

A2

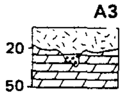


— permeable sand and gravel lying at or near land surface, usually more than 50 feet thick. Deposits are primarily of Wisconsinan age (Henry Formation). These deposits are found along most major rivers; those overlain by modern alluvium have been mapped as AX. Other deposits include thick Illinoian sand and gravel (Pearl Formation), the Mounds Gravel of Tertiary age, and sand and gravel of Cretaceous age (figs. 1 and 2).

Geologic limitations. The potential for contaminating wells finished in these materials is high. Also, contaminants may be discharged directly into nearby streams. Because hydraulic conductivity averages 1×10^{-3} cm/sec, contaminants migrate rapidly.

Principal counties. Wisconsinan sand and gravel is abundant in Boone, Bureau, Gallatin, McHenry, Henry, Iroquois, Kankakee, Lee, Mason, Whiteside, and Winnebago. Thick Illinoian sand and gravel occurs mostly in Christian, Fayette, and Montgomery Counties. Thick Tertiary and Cretaceous sand and gravel occurs in Massac, Pope, and Pulaski Counties.

A3



— permeable (fractured) Mississippian limestone or dolomite generally within 20 feet of the surface; sand and gravel occurs between 20 and 50 feet, wherever the bedrock is deeper than 20 feet.

Geologic limitations. The potential for contaminating shallow aquifers is high. In this geologic sequence, aquifers are slightly less susceptible to contamination than aquifers in sequences rated A1 and A2 because thick till or loess overlies bedrock in some parts of the A3 areas.

Principal counties. Adams and Rock Island.

Figure 18. Descriptions of Geologic Materials Following the Illinois Methodology
Source: Berg et al. (1984)

Step 6. Maps created in Step 5 are rated for hydrogeologic sensitivity by comparing mapped designations (A1, A2, etc.) to sensitivity ratings provided in the user's manual as shown in Figure 19.

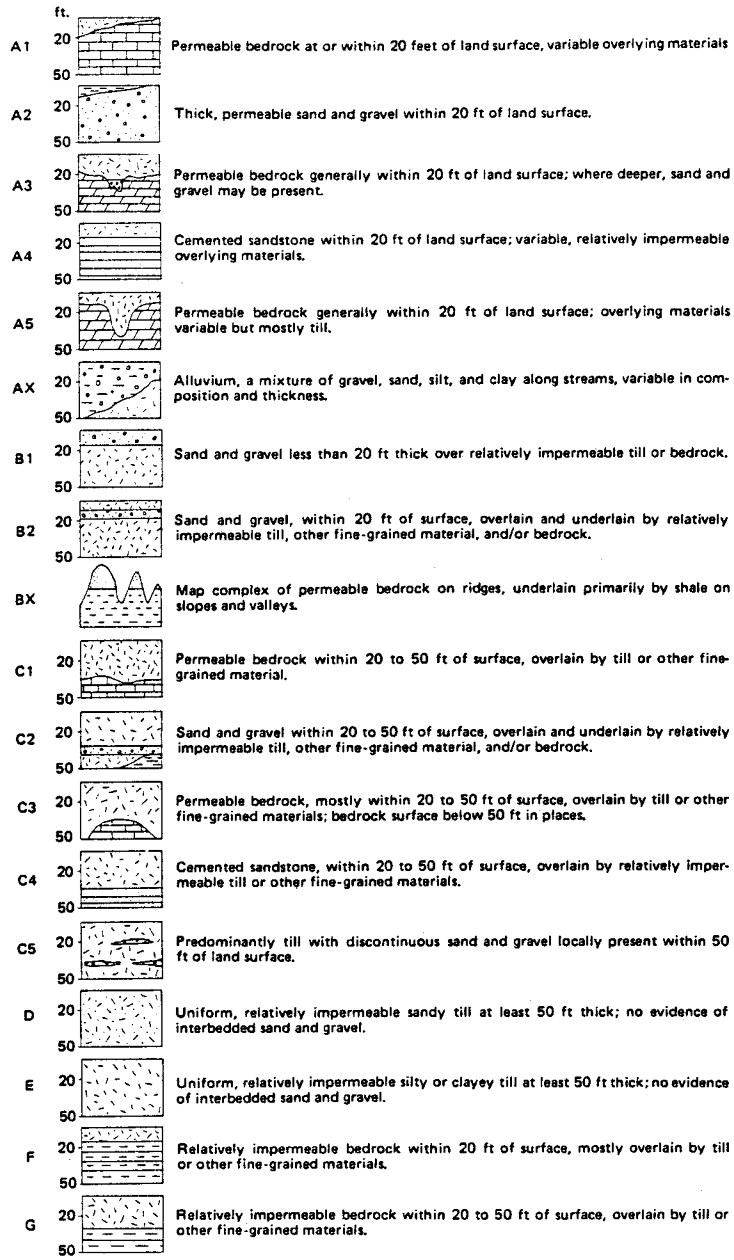


Figure 19. Examples of Ratings, Vertical Sequences, and Descriptions of Geologic Materials from the Illinois Methodology

Source: Berg et al. (1984)

METHOD OUTPUT

A regional scale map of geological units is created which can be used to estimate hydrogeologic sensitivity as shown in Figure 20. The map reflects distribution of earth materials both horizontally and vertically throughout the state in terms of specified geologic units which are pre-rated for hydrogeologic sensitivity.

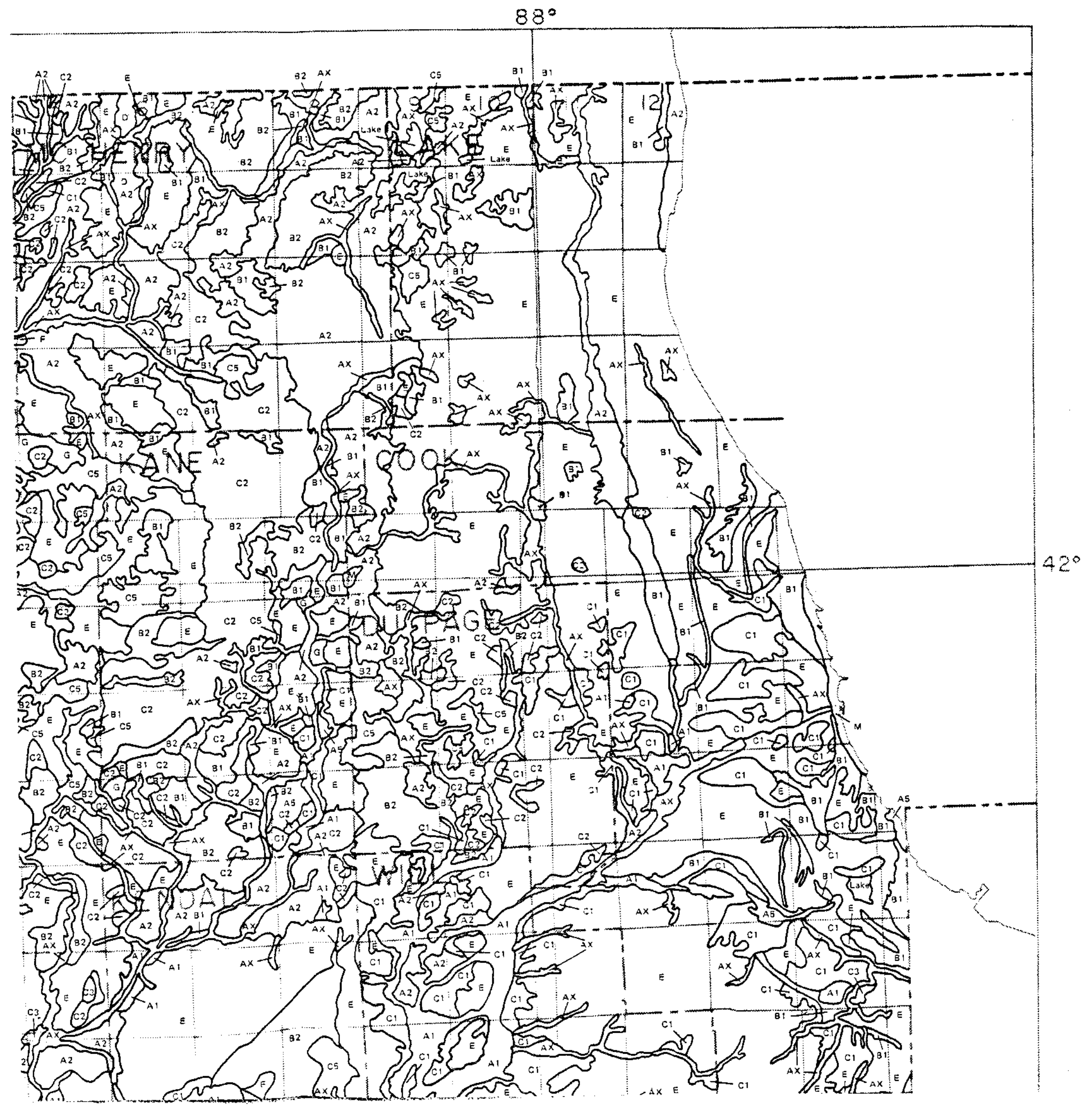


Figure 20. Illinois Contamination Potential Map (Chicago Area)
Source: Berg et al. (1984)

LIMITATIONS OF THE METHOD

1. The method evaluates only hydrogeologic sensitivity. Since contaminant behavior is not considered, the rating scheme is only applicable to non-hazardous municipal waste.

2. It is only applicable to a 50 foot depth -- deep aquifers are not included.

3. It is not appropriate for site specific evaluation. The small scale maps used in this evaluation are not precise enough for site specific application.

4. It is not appropriate for evaluating sites requiring long periods of containment (e.g., radioactive wastes).

Primary source: Berg et al. (1984). *Secondary source:* Trojan (1986).

3.2 HYDROGEOLOGIC SENSITIVITY AND CONTAMINANT BEHAVIOR

3.2.1 TROJAN/PERRY METHOD

GENERAL PURPOSE

The Trojan/Perry Method estimates ground water sensitivity to contamination over large geographic areas based on a variable number of factors. A general equation is developed that incorporates as many factors as available data allow. Thus, the index is very flexible. It can be used solely as an indicator of general hydrogeologic sensitivity, but waste characteristics and attenuation factors can be incorporated as data allow.

SCALE

This method is designed for use on a regional scale.

METHOD OVERVIEW

The Trojan/Perry Method is different than other existing methodologies. Most rating systems provide standardized rating schemes for a predetermined number of factors. Application of most methods involves a fixed number of steps that systematically rate a fixed number of factors. For example, LeGrand (1983) consists of 4 stages and 10 systematic steps for rating each site. Data requirements and analysis procedures are predetermined.

The Trojan/Perry method is not standardized. Users design their own rating system based on available information, professional expertise, and time/budgetary constraints. The system can evaluate any number of factors from a particular site by utilizing one of two generalized equations:

equation 1a:

$$HI = R\frac{(WaAb...n + WbBab...n + WnNab...n)}{Wa + Wb + ... Wn}$$

equation 1b:

$$HI = \frac{(WrRab...n + WaAab...n + WnNab...n)}{Wr + Wa + ... Wn}$$

where:

HI = Hazard Index for a site
R = water available for recharge
Wa,Wb,Wn = weights for factors A, B, and N
A,B,...N = factor scores for A,B, and N
a,b,...n = identifiers and correctors for factors

These equations incorporate as many or few factors as user needs and available data allow.

Development of weights and factors for use in these equations involves a 5 step approach:

1. Define specific objectives. Examples include,
   a) develop a system to estimate ground water sensitivity to a class of pesticides.
   b) develop a system to identify areas which are favorable for low-level waste sites.
2. Determine factors needed for analysis. Important factors include recharge, soil permeability, depth to water table and sensitivity of vadose zone materials among others. Specific factors should be chosen according to specified objectives.
3. Determine data availability from existing records, maps, government documents and other sources.
4. Develop scales, weights, correction terms and identifiers.
5. Implement, test and refine the system.

DATA REQUIREMENTS

Due to the flexible nature of the analysis, no standard data requirements are listed. Instead, factor scoring procedures are developed by the user according to guidelines provided by the methodology. Scoring procedures and data requirements are flexible depending on the needs, resources and objectives of the user. Development of index scores follows general guidelines provided in the methodology. Six factors are explicitly discussed: recharge, vadose zone permeability, depth to water, infiltration, topography, and attenuation. The following outlines the development of these factor indices.

Recharge. The amount of water passed through the unsaturated zone into an aquifer during a specified period of time. Eight accepted methods of estimating recharge are outlined in the methodology. Other factors such as evapotranspiration and land use effects can be included. The user must decide which method to use depending on individual expertise, level of accuracy desired, available data and resources. Data requirements vary according to method used.

Factor scale development for recharge is based on a general water budget approach as follows:

$$R = P + I - PET$$

where:

R = recharge factor (inches/year)
P = precipitation (inches/year)
I = irrigation (inches/year)
PET = potential evapotranspiration (inches/year)

An example scale is shown in Figure 21.

Rating Score

0	1.	2	3	4	5	6	7	8	9	0
0	2	4	6	8	10	12	14	16	18	20

Recharge (inches/year)

Figure 21. Example of a Rating Scale for Recharge
Source: Trojan and Perry (1989)

Permeability of Vadose Zone. The Trojan/Perry Method presents permeability factor scales from existing ground water sensitivity techniques. It also outlines accepted methods for estimating permeability with which users can develop their own scales. Users decide which approach is appropriate depending on individual expertise, level of accuracy desired, available data and resources. Data requirements vary accordingly. Guidelines are provided in the manual for index development.

Depth to Water. Calculated by subtracting water table elevations from surface elevations using geologic maps, well logs, and topographic maps. Guidelines are provided in the manual for index development.

Infiltration Rate. Calculated in length per unit time based on average permeability of soil and geologic materials. The Trojan/Perry Method presents a brief literature review of accepted methods for permeability estimation. Users can either develop their own permeability estimates or use generalized estimates based on soil texture and structure. Guidelines are provided in the manual for index development.

Topography. The factor score is based on slope position determined from topographic maps. The rating scale is shown in Figure 22. Additional score modification is made according to slope percent. Information is gathered by color-coding existing topographic maps. General guidelines are provided for index development.

Rating Score

0	1	2	3	4	5	6	7	8	9	10
100	50	40	30	20	15	10	7	4	2	0

Slope (%)

Figure 22. Typical Topography Rating Score
Source: Trojan and Perry (1989)

Attenuation. General guidelines for determining attenuation factors are provided for four classes of contaminants: metals, radioactive wastes, nitrates/phosphorus, and organics. A literature review of attenuation studies and procedural guidelines are provided to help users develop attenuation indices.

METHOD OUTPUT

Site index scores calculated from the above equations are incorporated into a regional sensitivity map. Site indices serve as sample points for the larger regional map. For example, Trojan and Perry (1989) laid a dot grid over a regional map of Winona County, Minnesota (1:200,000). Distance between points in this study was 1/4 mile, but can vary depending on goals of the analysis and data available (Trojan and Perry, 1989). Site indices derived from maps, however, do <u>not</u> have sufficient resolution for site-specific analysis.

LIMITATIONS OF THE METHOD

1. Detailed evaluations using this system can be difficult and require considerable professional expertise in hydrogeology and soils. Professional judgement is needed because mathematical relationships among risk factors and correction terms have to be individually derived by the user based on local site conditions. For a rigorous analysis, local site conditions have to be developed for a number of sites over large geographic areas.

2. The system is only useful on water table aquifers. It is not applicable on confined or artesian aquifers.

3. Factor evaluations and indices are subjective and would not necessarily be consistent among different users.

4. The final index score and sensitivity map does not include uncertainty estimates. For example, assume a sensitivity map includes evaluations of two sites. Site 1 has an index score of 4 based on 5 factor scores and Site 2 has an index score of 4 based on 2 factors. Index scores would be computed as follows:

   Site 1: Index based on 5 factors

$$HI = 2 * \frac{(3 + 2 + 4 + 1)}{5} = 4$$

   assuming:
   recharge index = 2
   permeability index = 3
   depth to water index = 2
   infiltration index = 4
   topography index = 1
   all factor weights = 1

   Site 2: Index based on 2 factors

$$HI = \frac{1 * (4)}{1} = 4$$

   assuming:
   recharge index = 1
   permeability index = 4
   all factor weights = 1

Index scores from Sites 1 and 2 are identical and would represent points on the final sensitivity map. However, the Site 1 index would probably be more reliable because it includes more factor ratings than Site 2. The implicit uncertainty within each site index score based on number of factors included is not reflected in the final index or sensitivity map.

Primary source: Trojan and Perry (1988). *Secondary source:* Trojan and Perry (1989).

SECTION 4: CONTAMINANT INDICES

Methodologies referred to as Contaminant Indices rank relative ground water contamination potential among chemicals. They are useful tools for regulatory agencies in: 1) ranking large numbers of contaminants from which monitoring variables can be drawn, or 2) developing specific strategies for studying contaminant behavior. Methodologies are organized into two sub-categories as follows:

1. Methods that evaluate contaminant properties only
   a) Leaching Index

2. Methods that evaluate contaminant and soil properties
   a) Pesticide Index
   b) Pesticide Rating System

The Leaching Index (Laskowski et al., 1982) emphasizes chemical properties. It is easy to use but treats soil properties superficially. It only considers organic matter content and does not take application rate into account. Nevertheless, it would probably be useful in large, relatively homogenous areas where soil differences would not differentially affect contaminant behavior to a large degree. The Pesticide Index and the Pesticide Rating System evaluate chemical properties but also incorporate soil criteria into the evaluation. They would probably be more useful than the Pesticide Index in heterogenous areas where varying soil properties have a greater impact on contaminant behavior.

4.1 CONTAMINANT PROPERTIES ONLY

4.1.1 LEACHING INDEX

GENERAL PURPOSE

The Leaching Index ranks pesticides according to relative ground water contamination potential using chemical properties such as solubility, vapor pressure, and K_{oc}. In contrast to the Pesticide Index (Rao et al., 1985), this method does not take soil or hydrogeologic factors into account. It is not a predictive tool, but rather a simple method for ranking the relative potential of various pesticides to intrude into the ground water based solely on chemical properties. It makes no assumptions regarding the environment into which the chemical is placed, nor does it estimate absolute values for exposure levels.

This index is designed to help regulatory agencies make preliminary evaluations of large numbers of pesticides from which a subset would be used for developing ground water monitoring or site-specific studies.

SCALE

Scale is not applicable to this methodology.

METHOD OVERVIEW AND DATA REQUIREMENTS

The Leaching Index is applied in two steps. The user must first assemble necessary information on environmental properties for a series of chemicals. These properties can be obtained from chemistry handbooks or other existing sources. The user must then combine the information according to the equation:

$$LI = [(S)(t/2)]/[(Vp)(K_{oc})]$$

where:

- LI = leaching index
- S = water solubility (ppm) @ 25oC
- t/2 = soil degradation half life @ 25oC
- Vp = Vapor pressure (mm Hg) @ 25oC
- K_{oc} = soil-water partition coefficient (K_p) normalized to organic content (OC). (i.e., Koc = K_p/OC)

METHOD OUTPUT

This method results in an index score for a series of pesticides that can be ranked according to potential hazard and compared to other pesticides.

LIMITATIONS OF THE METHOD

The Leaching Index rests on several simplifying assumptions including:

1. Total movement within or from soil is assumed to be inversely proportional to the decomposition rate in the soil (i.e., half-life). However, site-specific environmental factors such as clay type, pH, redox potential and soil bacteria can cause the half-life of pesticides to vary within the same geologic medium and introduce error into the ranking.

2. Leaching rates through soil are assumed to be directly proportional to the quantity of chemical in soil water as estimated by water solubility (S). Different hydrogeologic mediums, however, can alter solubility behavior.

3. It is assumed that a K_{oc} value can be estimated for each pesticide. Consequently, this method is not applicable to ionic pesticides such as paraquat or diquat. In addition:

   a) K_{oc} estimates, which are based on K_p estimates, are highly variable from one source to another.
   b) Due to complex transport mechanisms in hydrogeologic media, simple K_p estimates are not always reliable indicators of actual contaminant transport.

4. It is assumed that pesticide degradation follows first-order kinetics. This is not true for organics under all hydrogeologic conditions.

5. The method assumes that chemicals will respond in direct proportion to their numerical rating in whatever environment they are placed, that is, relative ranking does not change from one environment to another. For example, if atrazine has a higher ranking than chlordane, the method assumes that atrazine will always migrate faster than chlordane, regardless of soil medium. This can be erroneous if heterogeneities exist within the soil medium.

Primary source: Laskowski et al. (1982). *Secondary source:* Rao et al. (1985).

4.2 CONTAMINANT AND SOIL PROPERTIES

4.2.1 PESTICIDE INDEX

GENERAL PURPOSE

The Pesticide Index was designed to rate relative ground water contamination potential of various pesticides by evaluating factors such as: 1) travel time and persistence; 2) pesticide mass emission leaching past the vadose zone; 3) pesticide concentration in ground water; and 4) persistence and dilution in the saturated zone. The Pesticide Index estimates travel times through both the crop root zone and the intermediate vadose zone, as well as estimating the mass emission (loading) into the ground water (Rao et al., 1985). The Index is not a predictive tool, but rather a simple method for ranking relative potential of various pesticides to intrude into the ground water. It is designed to help regulatory agencies make a preliminary evaluation of large numbers of pesticides from which a subset would be used for developing ground water monitoring or site-specific studies.

SCALE

Scale is not specifically applicable to this method. However, since the Index is based on various soil and vadose zone characteristics, scale of measurement would depend largely on the scale of relatively homogeneous soil units in the area. For example, a Pesticide Index developed for an area in Kansas would probably be applicable over a larger geographical area than one developed in southeastern Minnesota.

METHOD OVERVIEW

The Pesticide Index estimates pollution potential of various pesticides based on characteristics of the pesticide and travel time through the root zone and intermediate vadose zone between the soil and the water table. Estimates are developed using simple, easy-to-use equations provided in the method. Final products of the methodology are two indices of pesticide behavior which can be estimated, ranked and compared among different compounds. The two indices are:

1. (AF) -- estimated attenuation factor which serves as an index of mass emission of pesticide from the vadose zone. This estimate is based on application rate, chemical travel time and a first-order degradation rate coefficient of the compound. A simple equation for estimating (AF) is presented in the methodology and the necessary chemical information for a given pesticide is usually available from existing sources. Specific information regarding management practices and application rate is also required.

2. (RF) -- estimated retardation factor (RF) which serves as an index of partitioning behavior of the pesticide in the soil. This estimate is based on various soil properties and two chemical properties (see *Data Requirements* for more detail). For greatest accuracy, values for soil parameters should be determined from field sampling, but reasonable estimates could be derived from existing information such as a soil survey.

METHOD OUTPUT

This method produces two index scores for a given pesticide which can be compared to those of other pesticides.

DATA REQUIREMENTS

Data required for the Pesticide Index are listed below. Due to the nature of the index, any convenient units can be used as long as they are consistent among pesticides evaluated.

1. AF estimation:
   a) Amount of pesticide applied at the soil surface.
   b) First order degradation coefficient (k) of the pesticide.
   c) Estimated travel time of water from ground surface to the water table. This could require local data on annual rainfall, irrigation rates and annual evapotranspiration.

2. RF estimation:
   a) Soil properties
      i. Soil bulk density
      ii. Organic matter content of the soil
      iii. Field capacity of the soil
      iv. Air-filled porosity of the soil
   b) Pesticide properties
      i. Octanol/water partition coefficient (K_{oc}) of the pesticide
      ii. Henry's law coefficient of the pesticide (K_h)

LIMITATIONS OF THE METHOD

The Pesticide Index rests on several simplifying assumptions including:

1. Vertical homogeneity is assumed (i.e., vadose zone properties are independent of depth). Strongly layered geologic materials would introduce error into the estimate.

2. It is assumed that a good estimate of the average ground water recharge rate can be computed by local rainfall, irrigation and evapotranspiration data. This may or may not be accurate.

3. It is assumed that a K_{oc} value can be estimated for each pesticide. Consequently, this method is not applicable to ionic pesticides such as paraquat or diquat because K_{oc} values do not exist for such compounds.

4. It is assumed that pesticide degradation follows first-order kinetics. This is not true for organics under all hydrogeologic conditions.

5. The average half-life value is estimated for each pesticide from a simple formula ($t^{1/2} = 0.693/k$). Potential problems are two-fold. First, this oversimplified formula may not be accurate for all pesticides under all conditions. Site-specific environmental factors such as clay type and soil bacteria can affect contaminant half-life. Second, the first order degradation rate coefficient (k) may not be readily available for the range of pesticides encountered.

6. To simplify the calculations, the estimate of total travel time (tr) used in the method assumes that the travel time in the root zone is equal to travel time in the vadose zone. This is clearly not true in field situations, and it may or may not be adequate for development of an accurate index in other circumstances.

7. Similarly, the first-rate degradation coefficient (k) in the root zone is assumed equal to (k) in the lower vadose zone. This definitely is not true in field situations, primarily because of decreasing organic matter with depth. Good professional judgment must be used in applying the methodology.

Primary source: Rao et al (1985). *Secondary source:* Canter et al. (1987).

4.2.2 PESTICIDE RATING SYSTEM

GENERAL PURPOSE

The Pesticide Rating System was designed for site-specific rating of potential pesticide loss due to leaching and runoff on Minnesota soils. It is especially applicable for row-cropped agricultural land. By evaluating both chemical properties and soil characteristics, the system estimates the potential of individual pesticides to migrate offsite. This system is useful for helping managers decide which pesticides should be used on a particular land unit.

The system is extremely easy to use. The evaluation develops a migration potential rating based on information from two sources: 1) Pesticide Rating System outlined in Becker et al. (1989); and 2) Soil ratings obtained from SCS *Field Office Technical Guides*.[1]

SCALE

This method evaluates migration potential of pesticides according to site-specific soil properties.

METHOD OVERVIEW

The Pesticide Rating System evaluates migration potential according to pesticide and soil properties as shown in Table 13. Predetermined ratings for soils and pesticides are used. Pesticide leaching ratings for herbicides, insecticides, and fungicides are provided with the methodology according to brand name. Soil ratings can be obtained from SCS *Field Office Technical Guides*. The following is a summary of how the user estimates leaching and runoff potential.

Leaching Potential. Soil and pesticide ratings from the above sources are combined into a matrix as shown in Table 14. Soil ratings obtained from the SCS classified as high, intermediate, or nominal are entered on the vertical axis. Pesticide ratings classified as large, medium, or small are entered on the horizontal axis. Leaching potential is read from the center portion of the matrix.

Runoff Potential. The same procedure is followed for runoff potential as shown in Table 14. Data are derived from the same sources.

METHOD OUTPUT

The result of this method is a migration potential rating for a specific land unit. Classifications are defined as follows:

Potential 1. Pesticide has a high probability of leaching (or runoff) on that soil.

Potential 2. Pesticide may leach or run off, but additional on-site information is needed to determine the sensitivity of the water resource of concern.

Potential 3. Pesticide has a low probability of leaching or runoff.

---

[1]Guides are currently being made available on a county by county basis by the SCS throughout the state of Minnesota.

Table 13. Pesticide Rating System--Physical Properties and Migration Ratings for Some Common Pesticides

Brand Name	Common Name	Soil Sorption Index	Water Solubility	Soil Half-life	Rating for Movement by: Surface Runoff	Leaching
		(K_{oc})	(ppm)	(days)		
Alanap	naptalam	(pH)	(pH)	14	-	-
Ally	metsulfuron-methyl	(pH)	(pH)	120	-	-
Amiben	chloramben	(pH)	(pH)	14	-	-
Amitrol T	amitrole	100	360000	14	Medium	Medium
Antor	diethatyl-ethyl	1300	105	14	Medium	Small
Arsenal	imazapyr acid	5	11000	90	Small	Large
Arsenal	imazapyr amine	5	500000	90	Small	Large
Assert	imazethabenz	35	875	35	Medium	Large
Assure	quizalofop-ethyl	100000	(pH)	60	Large	Small
Atrazine	atrazine	100	33	60	Medium	Large
Avenge	difenzoquat	54500	760000	100	Large	Small
Balan	benefin	9000	0.1	40	Large	Small
Banvel	dicamba	2	500000	14	Small	Large
Basagran	bentazon	35	2300000	20	Medium	Large
Betamix	phenmedipham &	2740	4.7	36	Large	Small
	desmedipham	2000	8	30	Large	Small
Betanex	desmedipham	2000	8	30	Large	Small
Bicep	metolachlor &	200	530	20	Medium	Medium
	atrazine	100	33	60	Medium	Large
Bladex	cyanazine	190	170	14	Medium	Medium
Blazer	acifluoren	139	250000	30	Medium	Medium
Bronate	bromoxynil &	190	0.08	5	Medium	Small
	MCPA ester	1000	5	14	Medium	Small
Bronco	glyphosate &	24000	900000	47	Large	Small
	alachlor	170	240	15	Medium	Medium
Buckle	triallate &	2400	4	82	Large	Small
	trifluralin	7000	0.3	60	Large	Small
Buctril	bromoxynil	190	0.08	5	Medium	Small
Buctril-Atrazine	bromoxynil &	190	0.08	5	Medium	Small
	atrazine	100	33	60	Medium	Large

Source: Becker et al. (1989)

DATA REQUIREMENTS

1. Pesticide leaching potential ratings provided in the manual.
2. Pesticide runoff potential ratings provided in the manual.
3. Soil leaching potential ratings from the National Soils Data Base obtained through local/county SCS.
4. Soil runoff potential ratings from the National Soils Data Base obtained through local/county SCS.

Table 14. Pesticide Rating System Migration Potential Matrices

Soil Leaching Rating	Pesticide Leaching Ratings		
	Large	Medium	Small
High	Potential 1	Potential 1	Potential 2
Intermediate	Potential 1	Potential 2	Potential 3
Nominal	Potential 2	Potential 3	Potential 3

Soil Surface Loss Rating	Pesticide Surface Loss Ratings		
	Large	Medium	Small
High	Potential 1	Potential 1	Potential 2
Intermediate	Potential 1	Potential 2	Potential 3
Nominal	Potential 2	Potential 3	Potential 3

Source: Becker et al. (1989)

LIMITATIONS OF THE METHOD

1. Pesticide characteristics used in the rating [adsorption (K_{oc}), solubility (S), and half-life ($T_{1/2}$)] are only typical approximations. Local environmental conditions and soil and land use practices can cause wide variation. Ratings should be used as guidelines rather than rules.

2. Soil characteristics used in the rating (texture, organic matter, depth, and slope) can also vary depending on site-specific factors. Again, ratings should be used as guidelines rather than rules.

3. Soil and pesticide ratings provided with the methodology are subject to update. The most recent SCS sources and pesticide labels should be consulted.

4. This system was developed with row crops. It will likely be expanded to include different agricultural practices and systems.

Primary source: Becker et al. (1989).

SECTION 5: LAND TREATMENT SITE EVALUATION

Land Treatment methods of waste disposal involve spreading waste at or near the land surface. Success of land treatment is based on contaminant attenuation and decomposition within the upper few meters of earth material. These methods typically use soil parameters that evaluate the upper strata of earth material, but do not systematically evaluate lower vadose zone materials.

The methodologies described in this section are designed for hazardous waste land treatment (HWLT), sometimes referred to as degradable waste land treatment (DWLT). Hazardous wastes include heavy metals, aromatic hydrocarbons, polycyclic hydrocarbons, and other potentially dangerous substances. Non-hazardous wastes include sewage sludge and other degradable materials. Methodologies for each category are as follows:

1. Methods that evaluate hydrogeologic sensitivity only
   a) Fuller Land Treatment Methodology

2. Methods that evaluate hydrogeologic sensitivity and chemical behavior.
   a) Mobility/Degradation Index

Fuller (1984) developed a method of evaluating sites for DWLT facilities. The method evaluates only hydrogeologic sensitivity and is used as a screening tool for uncontaminated sites. The absence of contaminant behavior evaluation limits its usefulness on hazardous waste sites. The Mobility/ Degradation Index (Mahmood and Sims, 1986) includes contaminant properties and can be used either for preliminary site screening or prioritization of contaminated sites for remediation.

5.1 HYDROGEOLOGIC SENSITIVITY ONLY

5.1.1 FULLER LAND TREATMENT METHODOLOGY

GENERAL PURPOSE

The Fuller Land Treatment Methodology is designed to help the user select appropriate sites for DWLT facilities. These facilities are designed to attenuate wastes within the upper soil layers. The Fuller Method emphasizes soil properties within 5 meters of the surface. Objectives of the method are:

1. Provide the methodology for "selecting suitable sites for land treatment of selected wastes based on a numerical rating scheme of factors influencing pollutant retention and stability."

2. "Identify those site criteria which can be managed and operated for acceptable performance as a system to utilize the natural biological, chemical, and physical processes in the soil for the purpose of degrading, attenuating, or otherwise rendering innocuous those wastes receiving such treatment."

The method is useful for land use planning and similar applications where a screening and evaluation of potential waste sites is needed. The Fuller method estimates only hydrogeologic sensitivity of the site by incorporating estimates of topographic, hydrologic and soil parameters. Although the methodology claims to be applicable to hazardous waste sites, contaminant properties and behavior are not evaluated.

SCALE

This method is designed for use on individual sites.

METHOD OVERVIEW

The Fuller methodology involves 5 steps that move stepwise from a broad, initial screening of large geographic areas to detailed, site-specific analysis:

1. **Reconnaissance of perspective areas**. This is a broad, generalized initial screening of unacceptable sites based on geologic, hydrologic, soils and area classifications.

2. **Rating landscape and topographic characteristics.** After the initial screening, step 2 evaluates three factors on candidate sites: a) land surface slope; b) soil susceptibility to erosion; and c) necessary site modifications. Field testing is not required for steps (a) and (b) since most information is available from existing sources. Classification guidelines were developed by the SCS. Site modifications (c) include activities such as filling, vegetation clearing, diking, and barrier construction. Detailed information on site modifications is not required.

3. **Rating soil characteristics.** Step 3 requires more site-specific information than steps (1) or (2). The Fuller methodology puts considerable weight on soil parameters. Because good information on 8 soil characteristics is needed, field testing and verification is required.

4. **Rating hydrologic and hydrogeologic characteristics.** Information for estimating these factors can be gathered from existing sources such as maps and hydrogeologic atlases.

5. **Determination of a final site score**. The scores from 1-4 are summed.

METHOD OUTPUT

The Fuller Method produces an index score which gives a relative ranking among candidate waste sites as shown in Figure 23.

DATA REQUIREMENTS

Step 1: Preliminary Screening. Information required for preliminary screening is given on a work sheet in the manual as follows:

A. Unsuitable landforms
   i. Floodplains
   ii. Moraine
   iii. Drumlins
   iv. Filled valleys
   v. Coastal plains
   vi. Deltas
   vii. Tidal flats
   viii. Sand dunes

Characteristic Used in Evaluating LT Sites	Individual Score	Step Number	Step Scores
Reconnaissance for elimination of unsuitable sites	______	______	______
Prominent slope range	______		
Soil erosion	______		
Land capability class	______		
Land site modification	______	______	______
Soil salinity	______		
Hydraulic conductivity	______		
Available water holding capacity	______		
Drainage class	______		
Particle size distribution	______		
pH (Acidity)	______		
CEC (Cation exchange capacity)	______		
Soil depth	______		
Restrictive subsoil layer	______	______	______
Depth to groundwater	______		
Depth to seasonal high water table	______		
Depth to bedrock	______		
Groundwater quality	______	______	______
Sum			

LT Site Identification:______________________________

Relative Rank:__________________ Date Evaluated:__________

Evaluator(s):______________________________

Figure 23. Fuller Land Treatment Index Final Rating Sheet
Source: Fuller (1986)

B. Unsuitable geological formations
   i. Karst
   ii. Volcanic cinders
   iii. Rock outcrops
C. Unsuitable hydrologic formations
   i. Seasonal high water table
   ii. Wetlands
   iii. Distance from water supply

D. Unsuitable soils
   i. pH less that 5.5
   ii. Soil depth < 2 feet
   iii. Slope > 6%
   iv. Impermeable soil layers within 6 feet
   v. Excessively permeable soils (e.g., sands, gravels)
   vi. Saline or alkaline lands
   vii. Severe erosion potential

E. Miscellaneous
   i. Polluted or contaminated land
   ii. Upwind of population centers
   iii. Broken, stony land
   iv. Wilderness areas

Step 2: Landscape and Topography. Effects of four site characteristics on ground water sensitivity are estimated according to:

A. Land surface slope
B. Susceptibility to erosion
C. SCS Land Capability Classification
D. Site modifications necessary to assure hazardous waste confinement

Step 3: Rating of Soil Characteristics. Effects of eight soil characteristics (listed below) on ground water sensitivity are estimated. Field testing is required.

A. Particle size distribution
B. Hydraulic conductivity
C. Soil depth
D. Soil pH
E. Cation exchange capacity (CEC)
F. Drainage class
G. Available water holding capacity
H. Restrictive subsoil layer

Step 4: Rating Hydrologic and Hydrogeologic Characteristics. Effects of four characteristics on ground water sensitivity are estimated:[1]

A. Depth to bedrock
B. Depth to seasonal high water table
C. Depth to ground water including perched water and regional water levels
D. Ground water and surface water quality

Step 5: Final Site Evaluation. Sums factors for a final site score. No new information is added.

LIMITATIONS OF THE METHOD

1. The method is designed only for DWLT facilities in which waste is spread over the land surface. It evaluates only the upper 5 meters of soil properties.

2. The method is site-specific and limited to areas for which detailed soil information can be obtained.

[1]It is assumed that precipitation, evapotranspiration and other climatologic conditions affecting recharge have been taken into consideration in site selection, even though they are not explicitly incorporated into this method.

3. This method is useful on uncontaminated sites only. Waste characteristics and effects on users are not considered.

4. Like all methods that rate only geologic sensitivity, no consideration is given to properties or behavior of specific contaminants. The estimate of contaminant movement is based on the rate at which water moves through the geologic media and an estimate of the ability of the soil to attenuate/degrade organics.

5. Soil organic matter, an extremely important factor in organic waste attenuation, is not specifically incorporated into the method even though detailed soil information is required.

Primary source: Fuller (1984). *Secondary sources:* Fuller (1986) and Trojan (1986).

5.2 HYDROGEOLOGIC SENSITIVITY AND CONTAMINANT BEHAVIOR

5.2.1 MOBILITY/DEGRADATION INDEX

GENERAL PURPOSE

The Mobility/Degradation Index rates relative ground water contamination potential of wastes deposited in Hazardous Waste Land Treatment (HWLT) sites. This type of treatment involves applying waste into the upper layers of soil for degradation. The objective is to accomplish treatment within the upper 5 feet of the soil profile.

The index can be used to set treatment priorities for hazardous materials in a HWLT system. It is also useful for design and management of hazardous waste treatment systems, selection of treatment schemes for particular sites, and for treating previously contaminated soil.

SCALE

Scale is not specifically applicable to this method. However, since the index is based on soil characteristics, the scale of measurement would depend largely on the size of relatively homogeneous soil units.

METHOD OVERVIEW

The Mobility/Degradation Index is defined as the ratio between the time required for a pollutant front to travel through a soil treatment zone and the pollutant half-life in the soil medium. The equation used to evaluate the index is:

$$MDI = \frac{d_c \Theta_s R}{(24 V_d t_{1/2})}$$

where:

- MDI = mobility/degradation index
- d_c = depth of soil treatment zone (feet)
- Θ_s = saturation moisture content (%)
- R = retardation factor
- V_d = recharge rate
- $t_{1/2}$ = compound half-life in the soil medium

For best results, site-specific soil information should be used.

METHOD OUTPUT

This method produces an index score that can be compared to scores of other contaminants.

DATA REQUIREMENTS

Data required for the Mobility/Degradation Index are listed below. Any convenient units can be used if consistently applied.

1. Depth of soil
2. Saturation water content (%) -- method provides estimates for various soil textures
3. Retardation factor (R) -- estimated according to the equation:

$$R = \frac{1 + (p)(\%oc)(K_{oc})}{100(\Theta)}$$

where:

p = soil bulk density (g/cm^3)
%oc = percent soil organic carbon
K_{oc} = soil water partition coefficient normalized to organic matter content. Method provides several techniques for estimating K_{oc}.
Θ = soil water content

4. Recharge (inches/hour)
5. Contaminant half-life (days)

LIMITATIONS OF THE METHOD

1. This method was designed for use on HWLT sites. These sites typically depend on attenuation within the upper 5 feet of the soil profile.

2. A good estimate of average ground water recharge is needed.

3. It is assumed that K_{oc} can be estimated for each contaminant. Consequently, this method is not applicable to ionic contaminants. In addition, K_{oc} estimates in the literature can be quite variable.

4. It is assumed that contaminant degradation follows first-order kinetics. This is not true for organics under all hydrogeologic conditions.

5. Half-life estimates are variable and may not be accurate for all contaminants under all conditions. Site-specific environmental factors such as clay type and soil bacteria can affect the half-life of the contaminant. In addition, the first order degradation rate coefficient (k) may not be readily available for the range of compounds encountered.

Primary source: Mahmood and Sims (1986).

SECTION 6: OIL AND GAS FIELD POLLUTION POTENTIAL EVALUATION

Oil and gas field methodologies evaluate contamination potential of disposal and production wells. They are useful for setting well-plugging priorities according to pollution potential. Methods are designed to:

1. Rank operational or abandoned supply wells
   a) Method for Prioritization of Oil and Gas Wells

2. Rank salt water disposal wells including waterflooding operations
   a) Method for Prioritization of Brine Disposal Wells and Waterflooding Operations
   b) Brine Disposal Methodology

Fairchild et al. (1981) presents a methodology for ranking operational or abandoned production wells according to pollution potential. The method emphasizes well condition, well construction, and regulatory compliance, but does not consider hydrogeologic sensitivity.

Fairchild et al. (1981) also presents a methodology for prioritizing salt water disposal wells and waterflooding operations. It is similar to the production well methodology except that it incorporates injection pressure, injection quantity, ground water quality, and other pertinent variables into the evaluation. Neither method incorporates hydrogeologic factors. These methods would probably be most useful in situations where age or faulty well construction and maintenance present the greatest pollution hazard.

Western Michigan University (1981) also presents a methodology for evaluating salt water disposal wells. Unlike the above methodologies, it incorporates hydrogeologic factors while putting less emphasis on well construction and maintenance. Consequently, it would probably be more useful where hydrogeologic setting rather than well condition poses the greatest pollution hazard.

6.1 EXISTING AND ABANDONED PRODUCTION WELLS

6.1.1 METHOD FOR PRIORITIZATION OF OIL AND GAS WELLS

GENERAL PURPOSE

This methodology estimates pollution potential associated with oil and gas wells. It applies to operational wells, abandoned wells that are properly or improperly plugged, and "dry holes.[1]"

SCALE

The method rates individual wells. However, scores can be combined into aggregate scores for townships or sections.

[1]Drilled wells insufficient for oil or gas production.

METHOD OVERVIEW

This method rates 7 factors related to individual wells including number of years unplugged, age category, surface casing, drilling compliance with regulations, plugging compliance, well size (area), and chemical substances present. Most information on individual wells is derived from existing sources such as corporate and government records. The user must also obtain appropriate regulations governing field activities because the system rates regulatory compliance of existing wells. Regulatory standards used in the methodology were prescribed by the Oklahoma Corporation Commission and will vary from state to state.

Application of the methodology requires assigning point values to appropriate factors for each well. If information is missing, a maximum point value is assigned. The final score for each well is a summation of factor scores (100 points maximum).

METHOD OUTPUT

An index score is produced for individual wells which can be compared with scores from other wells. Scores can also be grouped by township or county.

DATA REQUIREMENTS

The 7 factors used in this method require the following information:

1. **Years unplugged** counted from year of initial drilling.
2. **Age category** based on regulations at the time of drilling. For example, wells drilled between 50 and 30 years ago may not have been as stringently regulated as those drilled from 30 to 10 years ago. Consequently, they would be put in a distinct age category. Oklahoma wells were grouped into four major categories, but this will vary from state to state.
3. **Surface casing** rates casing material near the ground surface.
4. **Drilling compliance** evaluates regulatory compliance of drilling activities at the time of drilling.
5. **Plugging compliance** evaluates whether or not wells meet plugging regulations.
6. **Uncemented production area** of well casing exposed to subsurface environment (i.e., surface area of the pipe).
7. **Chemical substances** used in drilling muds and associated chemicals.

LIMITATIONS OF THE METHOD

1. Factor evaluation does not consider hydrogeologic sensitivity of the well field, only individual well characteristics. Theoretically, two wells from different areas could have the same score, yet different pollution potentials depending on geologic setting.

2. Factor scores are based largely on compliance with regulations that existed at the time of drilling. Varying standards could introduce error.

3. The method relies heavily on existing corporate and government records regarding regulatory compliance in well construction. Inaccuracies in the information will introduce error into the estimates.

Primary source: Fairchild et al. (1981). *Secondary sources:* Canter (1985) and Fairchild and Canter (1986).

6.2 BRINE DISPOSAL WELLS AND WATERFLOODING OPERATIONS

6.2.1 METHOD FOR PRIORITIZATION OF BRINE DISPOSAL WELLS AND WATERFLOODING OPERATIONS

GENERAL PURPOSE

This methodology ranks salt water disposal wells in oil and gas fields according to pollution potential. It is similar to the method outlined in *Section 6.1.1*, except that it focuses on injection wells and water flooding operations rather than production wells. Consequently, additional factors have been added to account for additional pollution risks associated with injecting solutions back into the ground water system.

SCALE

The method rates individual wells. However, scores can be aggregated into scores for townships or sections.

METHOD OVERVIEW

This method rates the same 7 factors used to rate oil and gas production wells (Fairchild, 1981). It also rates 7 additional factors pertaining to injection wells. Most information is derived from existing sources such as corporate and government records. The user must also obtain regulations governing field activities because the rating system evaluates regulatory compliance of wells. Regulatory standards used were prescribed by the Oklahoma Corporation Commission and will vary from state to state.

Method application requires assigning specific point values to the appropriate factors for each well. If information is missing, a maximum point value is assigned. The final score for each well is a summation of factor scores (200 points maximum).

METHOD OUTPUT

An index score is produced for individual wells that can be compared with scores of other wells. Scores can also be grouped by township or county.

DATA REQUIREMENTS

The 14 factors used in this method require the following information:

1. **Years unplugged** counted from the year of initial drilling.
2. **Age category** based on the regulations at the time of drilling. For example, wells drilled between 50 and 30 years ago may not have been as stringently regulated as those drilled from 30 to 10 years ago. Consequently, they would be put in a distinct age category. Oklahoma wells were grouped into four major categories, but this will vary from state to state.
3. **Surface casing** rates casing material near the ground surface.
4. **Drilling compliance** evaluates regulatory compliance of drilling activities at the time of drilling.
5. **Plugging compliance** evaluates whether or not wells meet plugging regulations.
6. **Uncemented production area** of well casings exposed to the subsurface environment (i.e., surface area of the pipe).
7. **Chemical substances** used in drilling muds and materials.
8. **Fresh water well location** within 1/2 mile of the site.

9. **Ground water quality** defined as total dissolved solids (TDS).
10. **Injection quantity** of either brine or fresh water.
11. **Injection pressure** of brine or fresh water.
12. **Distance** -- injection interval and location of interval relative to overlying fresh water aquifer.
13. **Quality of injected water** indicated by TDS.
14. **Cumulative injection** of fluids over the period of operation.

LIMITATIONS OF THE METHOD

1. Factor evaluation does not consider hydrogeologic sensitivity of the well field environment, only of individual well characteristics. Theoretically, two wells from different areas could have the same score, yet different pollution potentials depending on the geologic setting.

2. Factor scores are based largely on compliance with regulations that existed at the time of drilling. Varying standards could introduce error.

3. The method relies heavily on existing corporate and government records regarding regulatory compliance. Inaccuracies in the information will introduce error into the estimates.

Primary source: Fairchild et al. (1981). *Secondary sources:* Canter (1985) and Fairchild and Canter (1986).

6.2.2 BRINE DISPOSAL METHODOLOGY

GENERAL PURPOSE

This methodology ranks salt water disposal wells in oil and gas fields according to pollution potential. It is similar to both methods presented by Fairchild (1981), except that it includes more geologic information and less information about individual well construction and condition.

SCALE

The method rates individual wells, however scores can be combined into aggregate scores for larger areas.

METHOD OVERVIEW AND DATA REQUIREMENTS

The user must evaluate seven factors related to the wells and the surrounding geology as shown in Figure 24. Factors are given numerical values and summed to produce a final score for the well. Factors include:

1. **Brine disposal method**
   a) Pits
   b) Injection wells
      i. annular wells (brine is injected between inner and outer casings in shallow geological formations)
      ii. wells in which brine is injected through the center casing
      iii. wells which have tubing and/or packers within the casing

2. **Total volume of brine disposed** (barrels). Ratings designated for factors in (1) above are increased in proportion to the total volume of brine injected. Classifications range from 1-500,000 barrels for pits and from 1-10,000,000 barrels for injection wells. If the brine is discharged directly into an aquifer or injected under pressure, the factor score is increased by a designated multiplier.

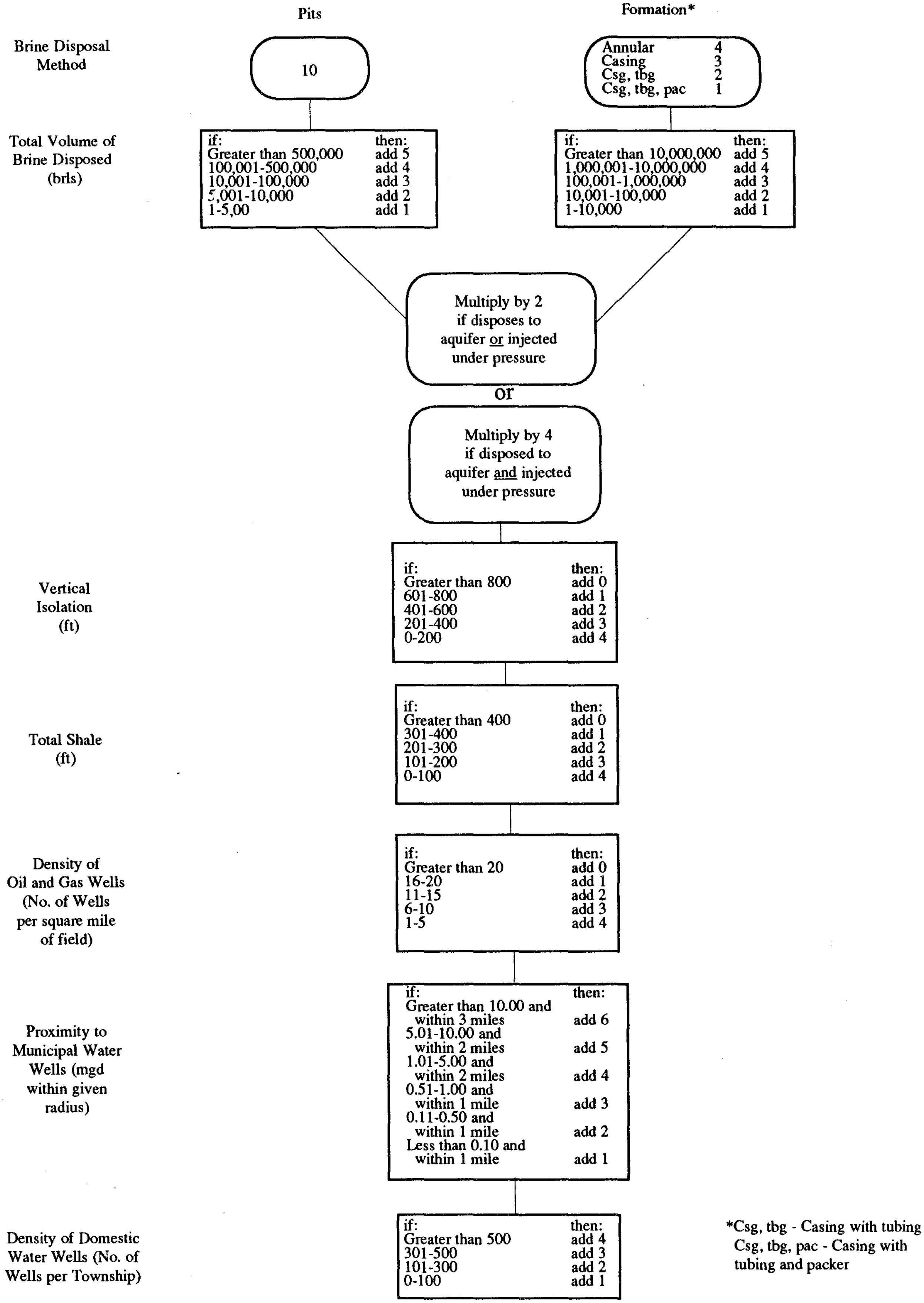


Figure 24. Brine Disposal Methodology Factors and Ratings
Source: Western Michigan University (1981)

3. **Vertical isolation** (feet) determined from well logs.

4. **Shale thickness** (feet) determined from well logs.

5. **Density of oil and gas wells** (wells per square mile)

6. **Proximity to municipal water wells** including both proximity (miles) and production rate of municipal wells (mgd) determined from public well records.

7. **Density of domestic water wells**--number of wells per township. Also available from public records.

METHOD OUTPUT

An index score is produced for each individual well which can be compared with other wells. The scores can also be grouped for larger areas.

LIMITATIONS OF THE METHOD

1. This method incorporates more geologic and less well information than other methods. Consequently, it would be of less value in areas where well construction was suspect.

2. This method is more general in scope that the methodologies presented by Fairchild (1981). Less emphasis is placed on the condition of individual wells. Wells in poor repair could receive the same score as wells in good repair even though the former present more of a pollution hazard.

3. If appropriate records aren't available, subjective estimates have to be made. Considerable error can be introduced, especially with regard to older wells.

4. Factor scores do not consider regulatory compliance.

5. The method relies heavily on existing corporate and government records regarding compliance with regulations in well construction. Inaccuracies in the information will introduce error into the estimates.

Primary source: Western Michigan University (1981). *Secondary source:* Canter (1985).

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