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DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings

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DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings

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Notice

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Foreword

The U.S. Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques and new technologies through which optimum use of the Nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of the facilities, the Robert S. Kerr Environmental Research Laboratory is the Agency's center of expertise for investigation of the soil and subsurface environment. Personnel at the laboratory are responsible for management of research programs to: (a) determine the fate, transport and transformation rates of pollutants in the soil, the unsaturated zone and the saturated zones of the subsurface environment; (b) define the processes to be used in characterizing the soil and subsurface environment as a receptor of pollutants; (c) develop techniques for predicting the effect of pollutants on ground water, soil and indigenous organisms; and (d) define and demonstrate the applicability and limitations of using natural processes, indigenous to the soil and subsurface environment, for the protection of this resource.

This report contributes to that knowledge which is essential in order for EPA to establish and enforce pollution control standards which are reasonable, cost effective and provide adequate environmental protection for the American public.

Clinton W. Hall

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Director
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Abstract

A methodology is described that will allow the pollution potential of any hydrogeologic setting to be systematically evaluated anywhere in the United States. The system has two major portions: the designation of mappable units, termed hydrogeologic settings, and the superposition of a relative rating system called DRASTIC.

Hydrogeologic settings are described for different regions in the United States. These settings incorporate the major hydrogeologic factors which affect and control ground-water movement including depth to water table, net recharge, aquifer media, soil media, topography, impact of the vadose zone and hydraulic conductivity of the aquifer. These factors, which form the acronym DRASTIC, are used to infer the potential for contaminants to enter ground water. These settings form the basis for the entire system and create units which can be graphically displayed on a map.

The relative ranking scheme uses a combination of weights and ratings to produce a numerical value, called the DRASTIC INDEX, which helps prioritize areas with respect to ground-water contamination vulnerability. The entire system optimizes the use of existing data and provides an evaluation which can be used to direct resources and waste disposal activities to appropirate areas.

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Acknowledgements

This document creates a standardized system which can be used to evaluate ground-water pollution potential. At the inception of the project, the implications for use of such a system were realized and a technical advisory committee was assembled. Prominent individuals with ground-water expertise respresented federal and state agencies, the Canadian government and private consultants. Throughout the development of the system, the committee provided guidance and direction. The document is a result of the synthesis of many approaches and opinions of individual committee members. Although each of the individuals contributed positively and effectively to the process, this report is a product of the National Water Well Association and is not endorsed entirely by each of the committee members. Successful completion of the project is due to the time and effort which an unusually able advisory committee was willing to devote to this activity. To the following named persons, grateful acknowledgement of their contributions is made:

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The basic conceptual foundation for this system is modeled after a waste disposal site evaluation technique developed by Harry LeGrand. The geographic framework for the presented system is developed within ground-water regions as defined by Ralph C. Heath. A special note of acknowledgement and gratitude is made to those two individuals for their inspiration and assistance in developing this document.

Section 1
Introduction

Objectives and Scope

The purpose of this project is to create a methodology that will permit the ground-water pollution potential of any hydrogeologic setting to be systematically evaluated with existing information anywhere in the United States. This document has been prepared to assist planners, managers, and administrators in the task of evaluating the relative vulnerability of areas to ground-water contamination from various sources of pollution. Once this evaluation is complete, it can be used to help direct resources, waste disposal, and other land-use activities to the appropriate areas. This document will also be useful to industry personnel who desire to understand the relationship between various practices and the ground-water pollution potential associated with them and to university personnel who teach the fundamentals of hydrogeology and ground-water contamination. It has been assumed that the reader has only a basic knowledge of hydrogeology and the processes which govern ground-water contamination. However, the greater the experience of the user, the more useful the system will become because the system can expand to be beneficial at any level of expertise. This report is not designed or intended to replace on-site inspections, or specifically to site any type of industrial facility or practice. Rather, it is intended to provide a basis for comparative evaluation of areas with respect to potential for pollution of ground water.

The scope of this project includes not only the development of a standardized system for evaluating pollution potential but also the creation of a system which can be readily displayed on maps. For purposes of mapping, the United States has been divided into hydrogeologic settings. These settings incorporate the many hydrogeologic factors which will influence the vulnerability of that setting to ground-water pollution. The settings have been chosen to represent areas larger than 100 acres in size, thereby limiting the system to use as a screening tool and not as a site assessment methodology.

The scope of this project does not include producing pollution potential maps of the entire United States. Rather, a set of demonstration maps will be prepared to show how the system could display the information on a map for ease of use and reference. Inherent in this demonstration is the idea that the standardized system cannot be finalized until it has been extensively tested in a wide variety of representative settings. Therefore, this system and the setting descriptions will be continually evolving until the demonstration project is complete.

In the formulation of this document an attempt was made to try to assimilate the thought processes of knowledgable professional hydrogeologists when evaluating the ground-water pollution potential of any area. From this thought process a simple-to-use and easy-to-understand methodology has been developed. It is important to remember that this document is intended to be used as a screening tool and is not intended to replace the need for professional expertise and field work in assessing the pollution potential in specific areas.

The system has been designed to use information which is available through a variety of sources. Information on the parameters, including the depth to water in an area, net recharge, aquifer media, soil media, general topography or slope, vadose zone media, and hydraulic conductivity of the aquifer is necessary to evaluate the ground-water pollution potential of any area using hydrogeologic settings. Although much of this information is available in existing reports, some might require estimation. In choosing parameters for which information is already available in some form, this system does not include many parameters and types of information which would be available from a more detailed site investigation. Therefore, it is important to realize that this document provides only a general, broad assessment to be used to evaluate sites for potential pollution.

To help illustrate two potential uses of this document, examples have been included: (1) When a professional hydrogeologist is asked to recommend the most hydrogeologically acceptable site for municipal waste disposal in a county area, he begins by reviewing many types of different information. From the information, he immediately rejects sites which are obviously unsuitable and continues to narrow his focus until a number of the most promising areas are identified. He will usually then recommend that more detailed information be obtained and/or site investigations be made on the most promising areas before any type of further action is taken. This is analogous to the purpose of this document. It provides the user with an idea of where to direct resources for further evaluation. (2) When state or local administrators have limited resources available to devote to ground-water protection, they are forced to focus these resources in certain areas. The system presented in this document helps identify areas which are more or less vulnerable than others to contamination. This delineation allows administrators to direct their resources to those more vulnerable areas most critical to the management problems, thereby making the most of the limited resources which are available.

Project Background

With the scope of the project in mind it is necessary to understand the importance of this document. Ground water is clearly regarded to be one of our nation's most valuable resources. Americans have long depended on ground water for many uses, but the primary use has been as a source of drinking water. Over 90 percent of the nation's public water supplies obtain their source water from ground water (Lappenbusch, 1984). Additionally, 97 percent of the water needs for domestic use in rural areas is served by ground-water resources (Solley et al., 1983).

National reliance on ground water has increased dramatically over the past 20 years. In the last 10 years alone, ground-water use has increased almost 30 percent while surface water withdrawals have increased only 15 percent (Solley et al., 1983). It is anticipated that the nation's reliance on ground water will continue to increase as demand for water increases in the future.

Concomitant with our reliance on ground water has come the need to protect our ground-water resources from contamination. Although contamination due to man has occurred for centuries, only in the past few years has the nation become aware of the dangers of ground-water contamination and of the many ways in which ground water can become contaminated. Moreover, in recent decades, the diversity of potential pollutants produced and used by man has increased dramatically. Since 1974, the Congress of the United States has been making an attempt to protect the nation's ground-water resources through legislation. The Safe Drinking Water Act (SDWA) (Public Law 93-523) mandated the establishment of drinking water standards to protect the public health, established the underground injection control (UIC) program to protect underground sources of drinking water from subsurface injection of wastes through wells, and established the Sole-Source Aquifer program. The Resource Conservation and Recovery Act (RCRA) (Public Law 94-580), passed in October 1976 and amended in November 1982, is the legislation which controls the management and disposal of solid and hazardous waste in such a manner that ground water will not be contaminated. The amended Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) (Public Law 92-516) as first passed in October 1972 and amended in 1975 and 1978, allows EPA to prohibit or mitigate ground-water contamination by pesticides by denying registrations, by modifying application methods, and through cancellations and suspensions of pesticides registrations. FIFRA also explicitly requires EPA to monitor environmental pollution. The Toxic Substances Control Act (TSCA) (Public Law 94-469), signed into law in October 1976, has no direct impact on ground-water protection but has the potential to be used as a mechanism in ground-water protection because the Act provides EPA with the power to regulate the use and manufacture of specific chemicals, some of which may pose ground-water contamination potential. The Surface Mining Control and Reclamation Act (SMCRA) of 1977 is the legislation which controls environmental impacts resulting from all mining activities. By establishing standards for these facilities, ground water may once again be protected. Finally, the Comprehensive Emergency Response Compensation and Liability Act (CERCLA) also known as "Superfund" provides a mechanism for the clean-up of ground water which has been contaminated at abandoned hazardous waste sites. A more complete discussion of these acts and their provisions which relate to ground water is given by Lehr, et al. (1984). This host of legislative measures has sought to help prevent the pollution of ground water in the future and to help mitigate some of the problems which have been created in the past.

Because prevention is the key to helping ensure that future practices do not result in ground-water contamination, it is now more important than ever to use planning and management tools to help recognize the places where certain activities pose a higher risk. This document addresses this need by providing an approach which can be used to help direct resources to protect ground water for future generations.

Classification Systems

One of the fundamental needs of any natural science is the development of an effective system to group similar entities into categories. Well-established systems exist in the fields of botany, geology, and many other sciences (Joel, 1926). These systems permit an appropriately trained person to gain certain insight about an entity simply by knowing the appropriate category in which it is grouped.

This systematic and logical way of imposing an artificial system on natural entities has long been used in the field of geology also. For example, rocks have been classified according to origin and minerals grouped according to crystal systems. However, as a science expands and changes, so must the types of systems used to describe those characteristics which need to be studied. The field of hydrogeology is one area of geology which has only been overtly recognized since the term was coined by Lucas in 1879 (Davis and Dewiest, 1966). Since that time hydrogeology has expanded, from a discipline devoted to water occurrence and availability, to include the broad aspect of water quality and solute chemistry. Definition of water quality is fundamental to the protection of the ground-water resource from pollution.

The idea of an organized way to describe ground water systems is not new. Meinzer (1923) prepared a small-scale map of the United States showing general ground-water provinces. Thomas (1952) and Heath (1984) prepared similar but more detailed maps and descriptions which grouped aquifers mainly on their water-bearing characteristics within certain geographic areas. Blank and Schroeder (1973) attempted to classify aquifers based on the properties of rocks which affect ground water. Of all these systems, geographic ones have been more widely accepted as ways to describe the quantity of water which is available in various regions.

Some Existing Systems Which Evaluate Ground-Water Pollution Potential

Within the last 20 years the need to expand these systems or to create a new system to address ground-water quality has become evident. Many different systems have been developed to address site selection for waste disposal facilities such as sanitary landfills or liquid waste ponds. Among these, the LeGrand System (LeGrand, 1983) and the modified version used by the U.S. EPA in the Surface Impoundment Assessment (SIA) are probably the most well known. The LeGrand system uses numerical weighting to evaluate ground-water pollution potential from a given waste disposal site. By evaluating the site through a series of four stages, a description of the hydrogeology of the site, the relative aquifer sensitivity combined with the contaminant severity, the natural pollution potential presented at that site, and the engineering modifications which might change that potential are all evaluated.

The LeGrand system presupposes only a limited technical knowledge but encourages the user to become familiar with the concepts presented in the manual so that skilled judgements can be made in the subjective portion of the system. The similarities between sites are emphasized and the uniqueness of each site is downplayed.

The U.S. EPA methodology (U.S. EPA, 1983) uses the basic LeGrand System to define the hydrogeologic framework, but modifies the system to place emphasis on establishing a monitoring priority for the facility. Once the hydrogeologic characteristics have been rated, a table is used to define the monitoring priority. This priority may be adjusted by the rater using prescribed techniques. Once again only a limited technical knowledge is presupposed.

Other systems have been designed to tailor the results to more specific purposes. Thornthwaite and Mather (1957) and Fenn et al. (1975) developed water-balance methods to predict the leachate generation at solid waste disposal sites. This approach is based on the premise that by knowing the amount of infiltration into the landfill and the design of the cell, the leachate quantity for the landfill can be determined. The system is intended as a tool to be used by engineers in the early design phase of a facility.

Gibb et al. (1983) devised a rating scheme to establish priorities for existing waste disposal sites with respect to their threat to human health by ground water. Via ranking the site through four factors, (1) health risk of the waste and handling mode, (2) population at risk, (3) proximity to wells or aquifers, and (4) susceptibility of aquifers, a number that ranges from 0-100 was used to display the relative risk. The system was used in a specific 2-county assessment by technically qualified individuals.

Another rating scheme, developed by the Michigan Department of Natural Resources (1983), is designed to rank large numbers of sites in terms of risk of environmental contamination. By evaluating the five categories: (1) release potential, (2) environmental exposure, (3) targets, (4) chemical hazard, and (5) existing exposure, the user obtains a number ranging from 0 to 2000 points which evaluates the relative hazard of that site with respect to other sites in Michigan.

Seller and Canter (1980) evaluated seven empirical methods to determine their usefulness in predicting the ground-water pollution effects of a waste disposal facility at a particular site. The methods they reviewed included rating schemes, a decision tree approach, a matrix and a criteria-listing method. They determined that each method took into account the natural conditions and facility design and construction, but that each method was best applied to the specific situation for which it was designed.

This brief review of selected existing systems reveals that there are a number of methods that can be applied to site-specific situations or to evaluation of the pollution potential of existing sites. However, a planning tool is needed for use before the site-specific methods are employed. The system must (1) function as a management tool, (2) be simple and easy-to-use, (3) utilize available information, and (4) be able to be used by individuals with diverse backgrounds and levels of expertise. This document contains a system which attempts to meet these needs and to provide the planning tool necessary before site-specific evaluations.

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Section 2
Development of the System and Overview

The focus of this project is to create a system which can be used to evaluate the ground-water pollution potential of any area in the United States. The system presented herein has two major portions: the designation of mappable units, termed hydrogeologic settings; and the application of a scheme for relative ranking of hydrogeologic parameters, called DRASTIC, which helps the user evaluate the relative ground-water pollution potential of any hydrogeologic setting. Although the two parts of the system are interrelated, they are discussed separately in a logical progression.

At the inception of the project, the far-reaching implications of a standardized system for evaluating ground-water pollution potential were realized, and a broadly-based, highly qualified technical advisory committee was assembled to help direct this effort. Through the direction and help of many, and discussion of opinions and suggestions, this system has evolved to represent a compromise approach. Further reference to the role of the committee will be made in the section discussing the development of the DRASTIC Index. A list of committee members can be found in the acknowledgement section.

Hydrogeologic Settings

This document has been prepared using the concept of hydrogeologic settings. A hydrogeologic setting is a composite description of all the major geologic and hydrologic factors which affect and control ground-water movement into, through, and out of an area. It is defined as a mappable unit with common hydrogeologic characteristics, and as a consequence, common vulnerability to contamination by introduced pollutants. From these factors it is possible to make generalizations about both ground-water availability and ground-water pollution potential.

In order to assist users who may have a limited knowledge of hydrogeology, the entire standardized system for evaluating ground-water pollution potential has been developed within the framework of an existing classification system of ground-water regions of the United States. Heath (1984) divided the United States into 15 ground-water regions based on the features in a ground-water system which affect the occurrence and availability of ground water (Figure 1). These regions include:

1. Western Mountain Ranges
2. Alluvial Basins
3. Columbia Lava Plateau
4. Colorado Plateau and Wyoming Basin
5. High Plains
6. Nonglaciated Central Region
7. Glaciated Central Region
8. Piedmont and Blue Ridge
9. Northeast and Superior Uplands
10. Atlantic and Gulf Coastal Plain
11. Southeast Coastal Plain
12. Alluvial Valleys
13. Hawaiian Islands
14. Alaska
15. Puerto Rico and Virgin Islands

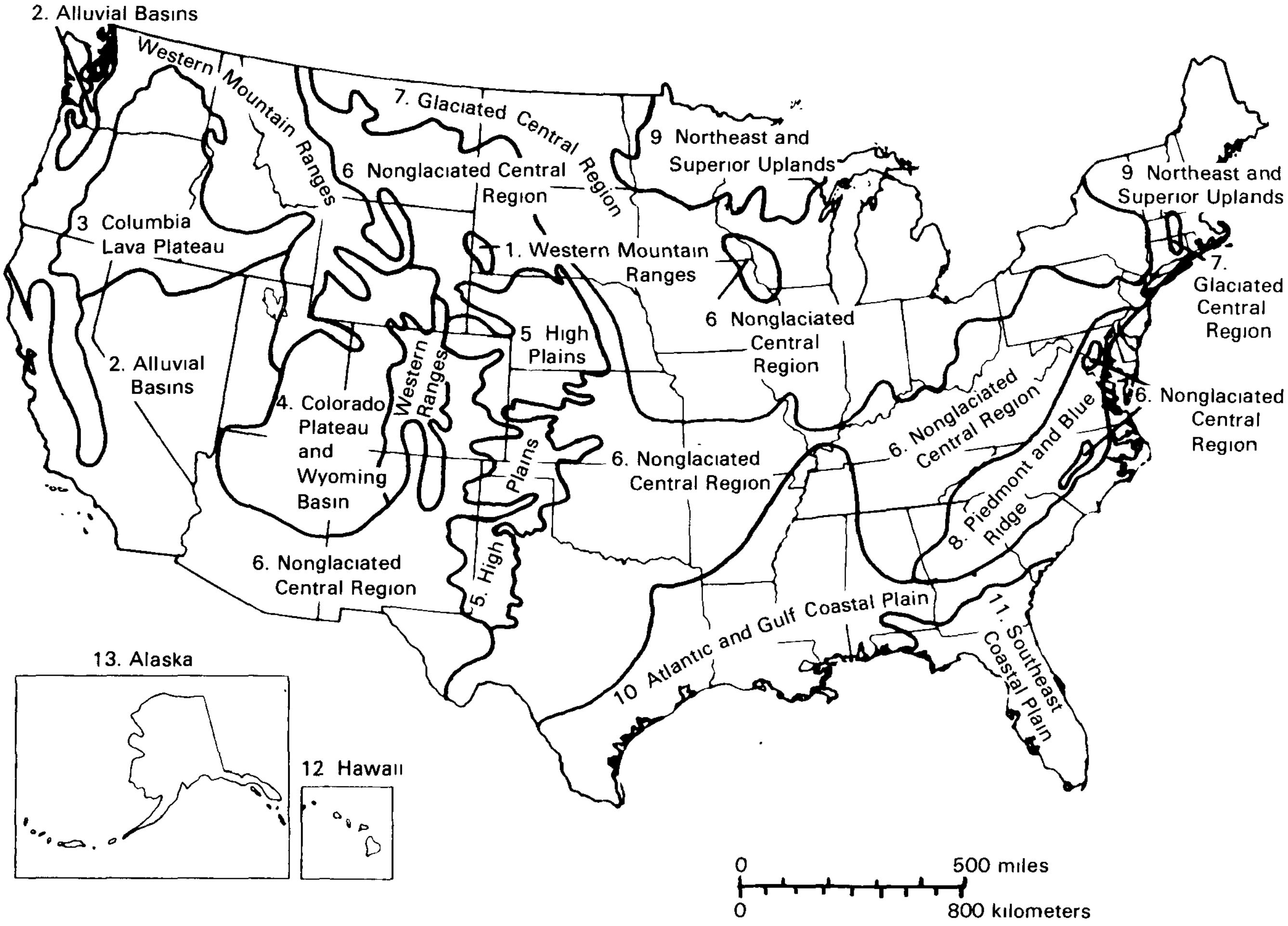
Region 12, Alluvial Valleys, is "distributed" throughout the United States.

For the purposes of the present system, Region 12 (Alluvial Valleys) has been reincorporated into each of the other regions and Region 15 (Puerto Rico and Virgin Islands) has been omitted. Since the factors which influence ground-water occurrence and availability also influence the pollution potential of an area, this regional framework is used to help familiarize the user with the basic hydrogeologic features of the region. An annotated description of each of the regions and the significant hydrogeologic factors are included in Section 9, Hydrogeologic Settings of the United States by Ground-Water Regions.

Because pollution potential cannot be determined on a regional scale, smaller "hydrogeologic settings" were developed within each of the regions described by Heath (1984). These hydrogeologic settings create units which are mappable and, at the same time, permit further delineation of the factors which affect pollution potential.

Each hydrogeologic setting is described in a written narrative section and illustrated in a block diagram. Figure 2 shows the format which is used throughout the document. The descriptions are used to help orient the user to typical geologic and hydrologic configurations which are found in each region and to help focus attention on significant parameters which are important in pollution potential assessment. The block diagram enables the user to visualize the described setting by indicating its geology, geomorphology, and hydrogeology.

Figure 1. **Ground-water regions of the United States (After Heath, 1984).**



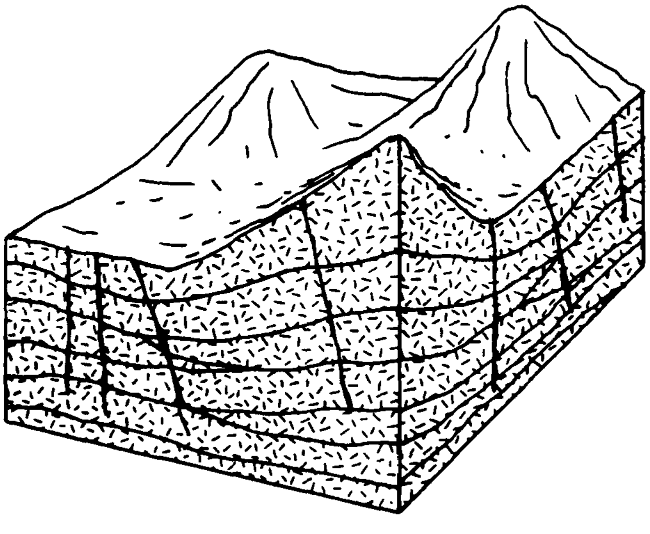
A set of hydrogeologic settings has been developed for each region. The document is designed so that once the broad geographic area is located, the user does not have to refer to other hydrogeologic settings in other regions. This means that similar hydrogeologic settings may appear more than once in the document, but that they have been tailored to reflect the typical hydrogeologic conditions within each individual region.

Hawaii

(12C) Volcanic Uplands

This hydrogeologic setting is characterized by moderately rolling topography, at medium elevations, and rich, dark, soils developed from the basaltic bedrock. The soils are permeable, rainfall is high, and recharge is high. Bedrock is composed primarily of alternating extrusive basaltic lava flows and interlayered weathered zones formed between flows. Ground water occurs at moderate to deep depths, and aquifer yield is controlled by fracture zones, vesicular zones (both primarily cooling features), and the inter-flow weathered zones. Hydraulic conductivity is high. As with other settings in Hawaii, heavy pumping stresses often result in salt-water intrusion. This is a reflection

Figure 2. **Format of hydrogeologic setting.**



of the fact that each island is surrounded by and underlain by salt water, with the fresh water occurring in a lenticular body that floats on the salt water. Ground water yield is therefore limited quite specifically to the amount of water recharged annually.

DRASTIC

Inherent in each hydrogeologic setting are the physical characteristics which affect the groundwater pollution potential. A wide range of technical positions was considered regarding the relative importance of the many physical characteristics that affect pollution potential. Factors including aquifer chemistry, temperature, transmissivity, tortuosity, gaseous phase transport, and others were evaluated. The availability of mappable data has also been considered. As a result of this evaluation, the most important mappable factors that control the groundwater pollution potential were determined to be:

D—Depth to water
R—(Net) Recharge
A—Aquifer Media
S—Soil Media
T—Topography (Slope)
I —Impact of the Vadose Zone
C—Conductivity (Hydraulic) of the Aquifer

These factors have been arranged to form the acronym, DRASTIC, for ease of reference. A complete description of the important mechanisms considered within each factor and a description of the significance of the factor are included in Section 3, DRASTIC: A Description of the Factors. While this list is not all inclusive, these factors, in combination, were determined to include the basic requirements needed to assess the general pollution potential of each hydrogeologic setting. The DRASTIC factors represent measurable parameters for which data are generally available from a variety of sources without detailed reconnaissance. Sources of this information are listed in Table 1.

A numerical ranking system to assess ground-water pollution potential in hydrogeologic settings has been devised using the DRASTIC factors. The system contains three significant parts: weights, ranges, and ratings. A description of the technique used for weights and ratings can be found in Dee et al., (1973).

Table 1. Sources of Hydrogeologic Information

Source	Depth to Water Table	Net Recharge	Aquifer Media	Soil Media	Topography	Impact of the Vadose Zone	Hydraulic Conductivity of the Aquifer
U.S. Geological Survey	X	X	X		X	X	X
State Geological Surveys	X	X	X			X	X
State Department of Natural/ Water Resources	X	X	X			X	X
U.S. Department of Agriculture-Soil Conservation Service		X		X	X		
State Department of Environmental Protection	X	X	X			X	X
Clean Water Act "208" and other Regional Planning Authorities	X	X	X			X	X
County and Regional Water Supply Agencies and Companies (private water suppliers)	X		X			X	X
Private Consulting Firms (hydrogeologic, engineering)	X		X			X	X
Related Industry Studies (mining, well drilling, quarrying, etc.)	X		X			X	
Professional Associations (Geological Society of America, National Water Well Association, American Geophysical Union)	X	X	X			X	X
Local Colleges and Universities (Departments of Geology, Earth Sciences, Civil Engineering)	X	X	X			X	X
Other Federal/State Agencies (Army Corps of Engineers, National Oceanic and Atmospheric Administration)	X	X	X			X	

(1) Weights—Each DRASTIC factor has been evaluated with respect to the other to determine the relative importance of each factor. Each DRASTIC factor has been assigned a relative weight ranging from 1 to 5 (Table 2). The most significant factors have weights of 5; the least significant, a weight of 1. This exercise was accomplished by the committee using a Delphi (consensus) approach. These weights are a constant and may not be changed. A second weight has been assigned to reflect the agricultural usage of herbicides and pesticides (Table 3). These weights are also constants and cannot be changed. A description of the usage of this second system can be found in Section 2 under the heading, "Agricultural DRASTIC."

Table 2. Assigned Weights for DRASTIC Features

Feature	Weight
Depth to Water Table	5
Net Recharge	4
Aquifer Media	3
Soil Media	2
Topography	1
Impact of the Vadose Zone	5
Hydraulic Conductivity of the Aquifer	3

Table 3. Assigned Weights for Agricultural DRASTIC Features

Feature	Agricultural Weight
Depth to Water Table	5
Net Recharge	4
Aquifer Media	3
Soil Media	5
Topography	3
Impact of the Vadose Zone	4
Hydraulic Conductivity of the Aquifer	2

(2) Ranges—Each DRASTIC factor has been divided into either ranges or significant media types which have an impact on pollution potential (Tables 4-10). A discussion of the media types is included in Section 3, Aquifer Media, Soil Media, and Impact of the Vadose Zone. The ranges and media types are graphed to show the linearity and non-linearity of the factor (Figures 3-9).

(3) Ratings—Each range for each DRASTIC factor has been evaluated with respect to the others to determine the relative significance of each range with respect to pollution potential. Based on the graphs, the range for each DRASTIC factor has been assigned a rating which varies between 1 and 10 (Tables 4-10). The factors of D, R, S, T, and C have been assigned one value per range. A and I have been assigned a "typical" rating and a variable rating. The variable rating allows the user to choose either a typical value or to adjust the value based on more specific knowledge. The ratings are the same for both the DRASTIC Index and the modified Agricultural DRASTIC Index.

This system allows the user to determine a numerical value for any hydrogeologic setting by using an additive model. The equation for determining the DRASTIC Index is:

$$D_RD_W + R_RR_W + A_RA_W + S_RS_W + T_RT_W + I_RI_W + C_RC_W = \text{Pollution Potential}$$

where:

R = rating
W = weight

Table 4. Ranges and Ratings for Depth to Water

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

Table 5. Ranges and Ratings for Net Recharge

Net Recharge (inches)	
Range	Rating
0-2	1
2-4	3
4-7	6
7-10	8
10+	9
Weight: 4	Agricultural Weight: 4

Table 6. Ranges and Ratings for Aquifer Media

Aquifer Media		
Range	Rating	Typical Rating
Massive Shale	1-3	2
Metamorphic/Igneous	2-5	3
Weathered Metamorphic/Igneous	3-5	4
Thin Bedded Sandstone, Limestone, Shale Sequences	5-9	6
Massive Sandstone	4-9	6
Massive Limestone	4-9	6
Sand and Gravel	6-9	8
Basalt	2-10	9
Karst Limestone	9-10	10
Weight: 3	Agricultural Weight: 3	

Table 7. Ranges and Ratings for Soil Media

Soil Media

Range	Rating
Thin or Absent	10
Gravel	10
Sand	9
Shrinking and/or Aggregated Clay	7
Sandy Loam	6
Loam	5
Silty Loam	4
Clay Loam	3
Nonshrinking and Nonaggregated Clay	1
Weight: 2	Agricultural Weight: 5

Table 8. Ranges and Ratings for Topography

Topography
(percent slope)

Range	Rating
0-2	10
2-6	9
6-12	5
12-18	3
18+	1
Weight: 1	Agricultural Weight: 3

Table 9. Ranges and Ratings for Impact of Vadose Zone Media

Impact of Vadose Zone Media

Range	Rating	Typical Rating
Silt/Clay	1-2	1
Shale	2-5	3
Limestone	2-7	6
Sandstone	4-8	6
Bedded Limestone, Sandstone, Shale	4-8	6
Sand and Gravel with significant Silt and Clay	4-8	6
Metamorphic/Igneous	2-8	4
Sand and Gravel	6-9	8
Basalt	2-10	9
Karst Limestone	8-10	10
Weight: 5	Agricultural Weight: 4	

Table 10. Ranges and Ratings for Hydraulic Conductivity

Hydraulic Conductivity
(GPD/FT^2)

Range	Rating
1-100	1
100-300	2
300-700	4
700-1000	6
1000-2000	8
2000+	10
Weight: 3	Agricultural Weight: 2

Once a DRASTIC Index has been computed, it is possible to identify areas which are more likely to be susceptible to ground-water contamination relative to one another. The higher the DRASTIC Index, the greater the ground-water pollution potential. The DRASTIC Index provides only a relative evaluation tool and is not designed to provide absolute answers. Therefore, the numbers generated in the DRASTIC Index and in the agricultural DRASTIC Index cannot be equated.

Figure 3 Graph of ranges and ratings for depth to water.

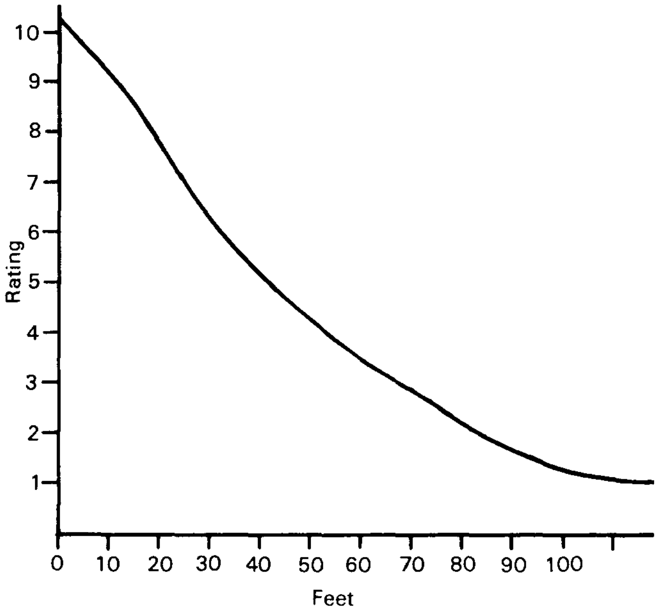
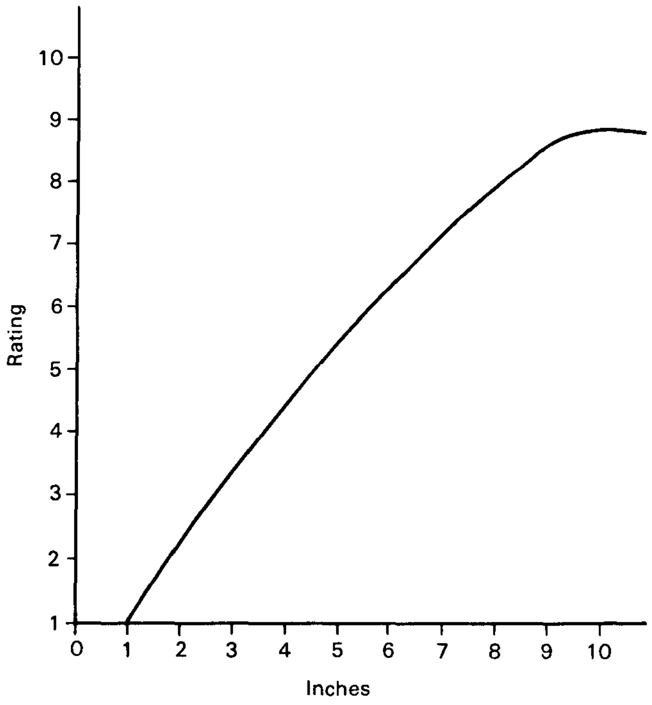


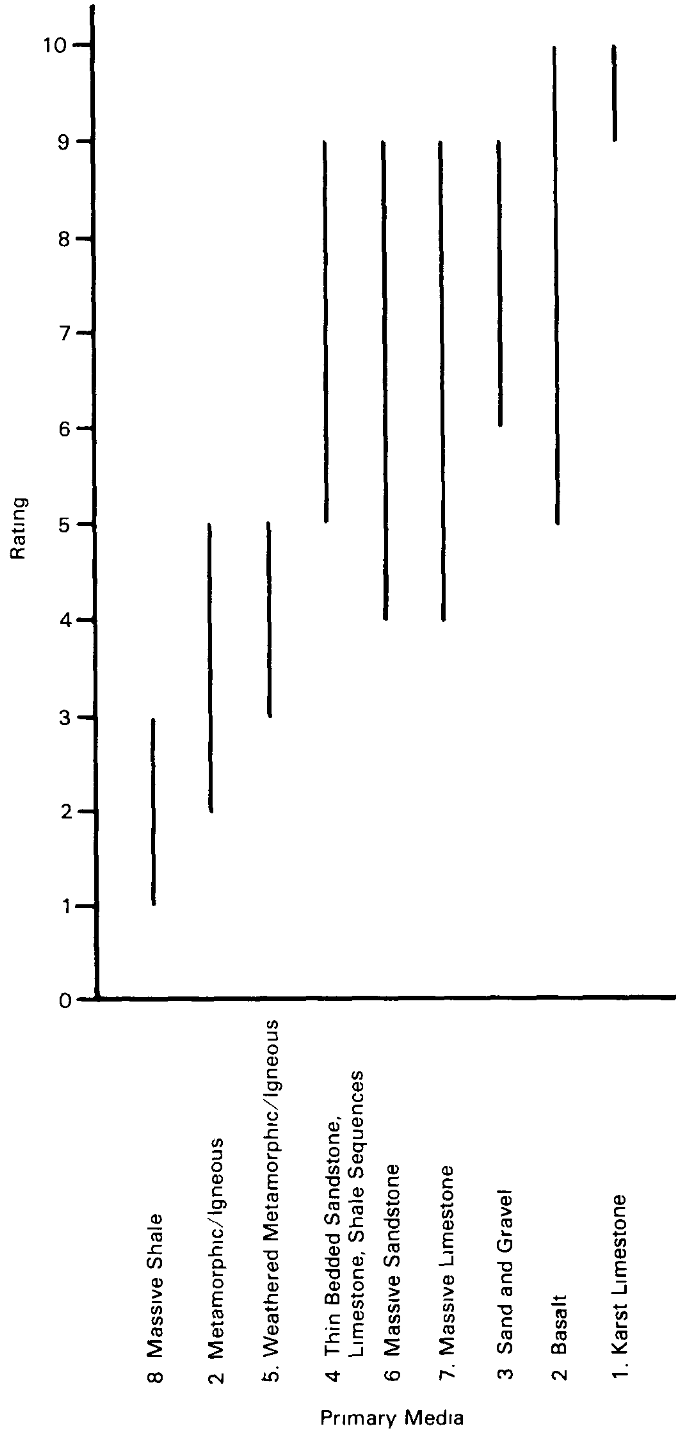
Figure 4. Graph of ranges and ratings for net recharge.



Agricultural DRASTIC

Agricultural DRASTIC is designed to be used where the activity of concern is the application of herbicides and pesticides to an area. It represents a special case of the DRASTIC Index. The only way in which Agricultural DRASTIC differs from DRASTIC is in the assignment of relative weights for the seven DRASTIC

Figure 5. Graph of ranges and ratings for aquifer media.



Relative ranges of ease of pollution for the principal aquifer types.

Ranges are based upon consideration of:
a) route length and tortuosity
b) potential for consumptive sorption
c) dispersion
d) reactivity and
e) degree of fracturing

Primary factors affecting rating:

1 Reactivity (solubility and fracturing)
2. Fracturing
3. Route length and tortuosity, sorption, dispersion. All essentially determined by grain size, sorting, and packing
4 Route length and tortuosity as determined by bedding and fracturing
5. Sorption and dispersion
6 Fracturing, route length and tortuosity, influenced by intergranular relationships
7. Reactivity (solubility) and fracturing
8 Fracturing and sorption

factors. All other parts of the two indexes are identical; the ranges, ratings, and instructions for use are the same. If the user is concerned with the ground-water pollution potential of an area by herbicides and pesticides, then the weights for Agricultural DRASTIC should be used.

Agricultural DRASTIC was created to address the important processes which specifically offset the fate and transport of herbicides and pesticides in the soil. These processes, however, may not be as significant when assigning weights to the other DRASTIC factors for non-agricultural activities. Thus, by comparing Tables 2 and 3, it can be seen that for non-agricultural activities, Soil Media is assigned a weight of 2, while for the modified Agricultural DRASTIC, the Soil Media is assigned a weight of 5. Topography, Impact of the Vadose Zone, and Hydraulic Conductivity of the Aquifer are also slightly different. By making these adjustments, the committee addressed the special conditions which influence the potential for ground-water contamination by pesticides and herbicides. It is important to note that the relative relationship between the DRASTIC factors was not deemed significantly different enough to warrant the development of any other modified DRASTIC indexes. The user should be reminded that weights may not be changed for any of the DRASTIC factors. These relative weights form the basis for the system and any changes will make the system invalid.

Figure 6. Graph of ranges and ratings for soil media.

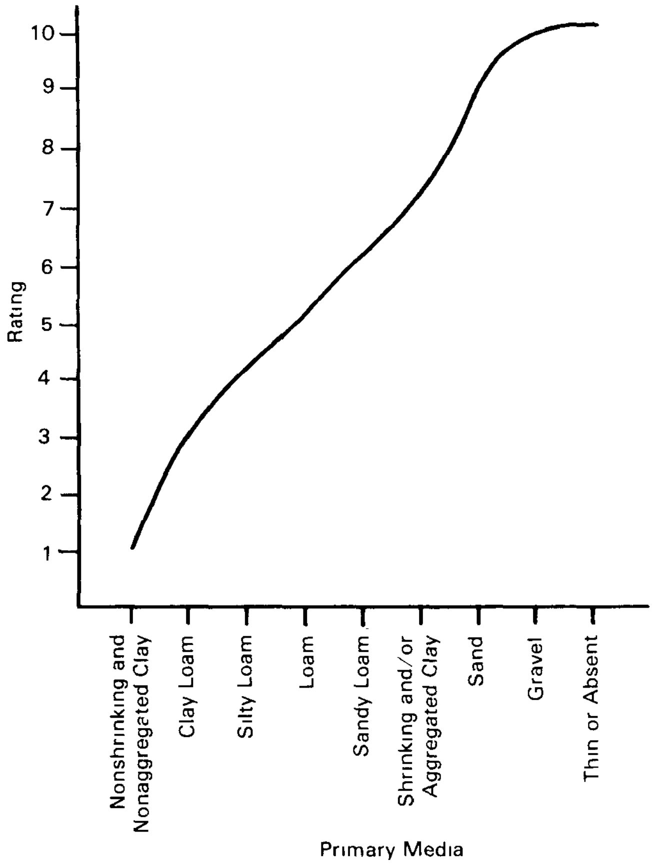
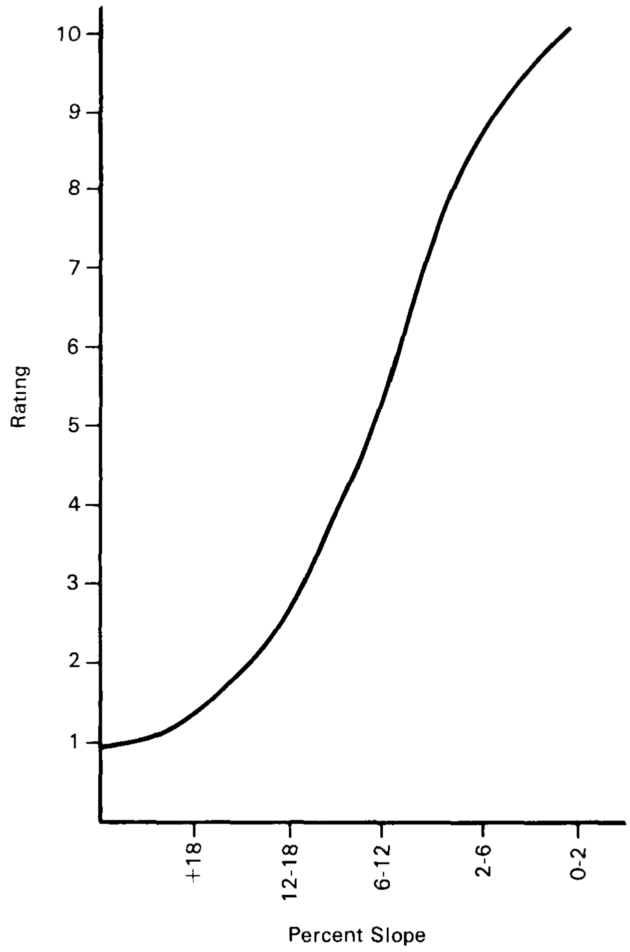


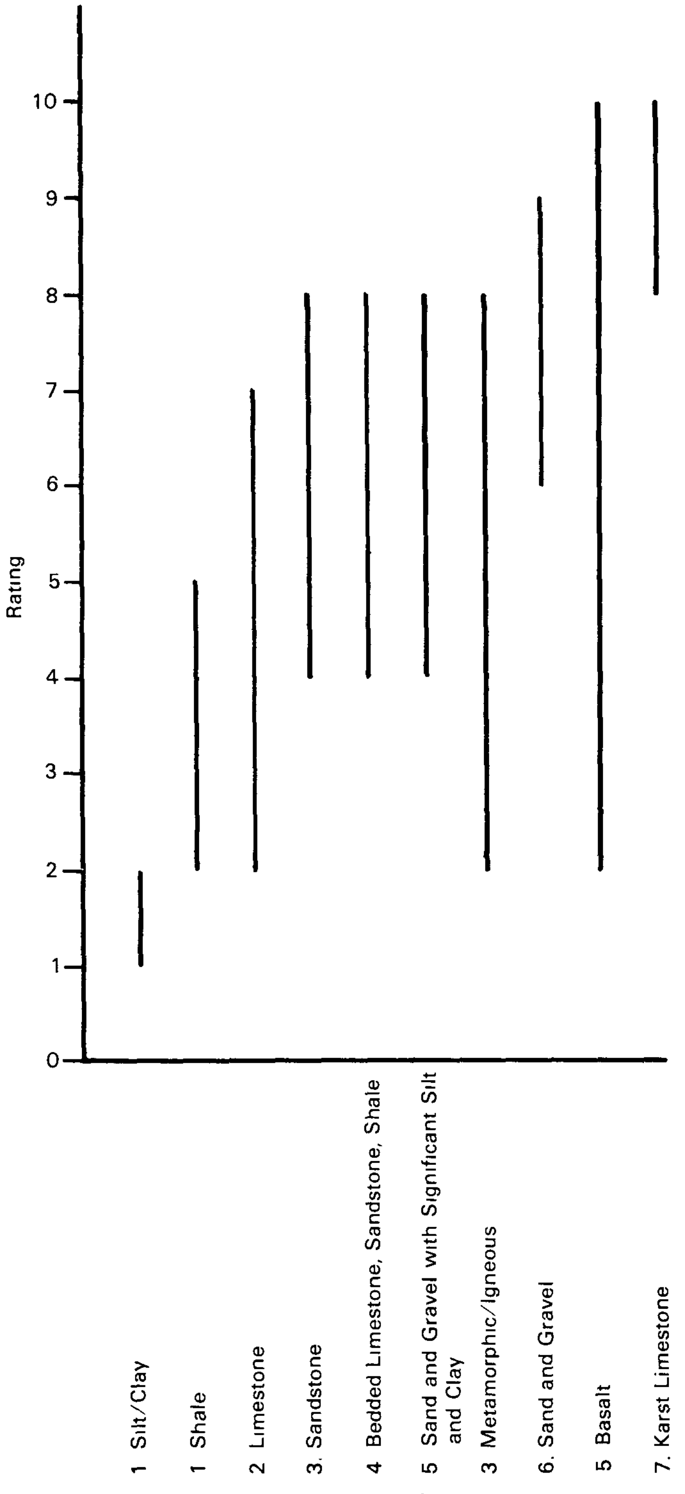
Figure 7. Graph of ranges and ratings for topography.



Integration of Hydrogeologic Settings and DRASTIC

The mappable hydrogeologic units and the DRASTIC Index have been combined to provide the user with a relative pollution potential for all typical hydrogeologic settings in the United States. A "typical" range for each DRASTIC factor is assigned to each hydrogeologic setting and a DRASTIC Index is determined for each typical hydrogeologic setting. These settings are developed as guides and are not designed to be representative of each and every area. The ranges for each factor may be adjusted by the user and the rating adjusted accordingly when available data indicate different conditions. These hydrogeologic settings

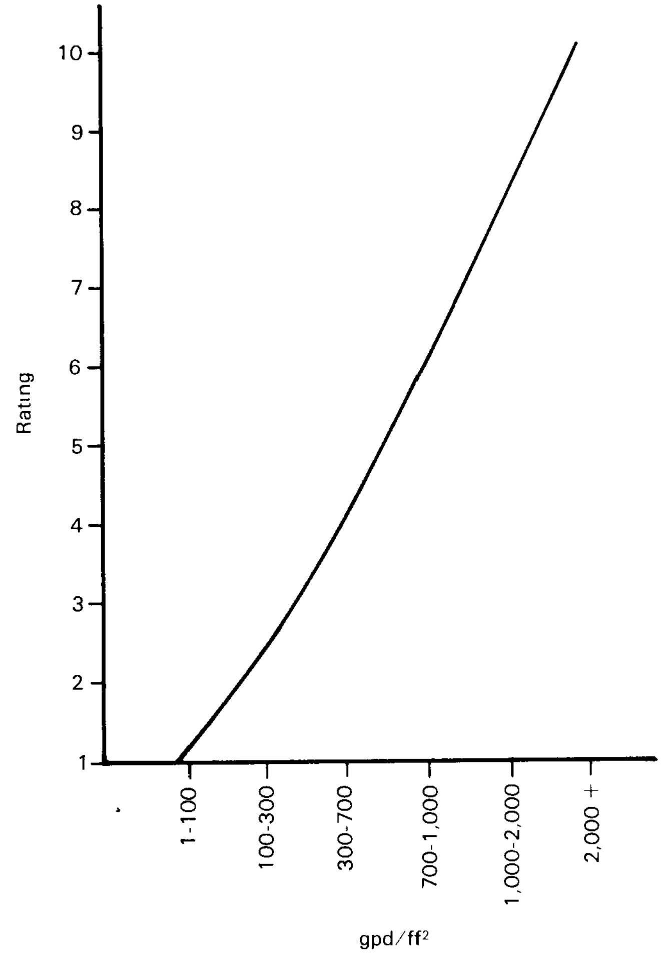
Figure 8. Graph of ranges and ratings for impact of the vadose zone



Relative impact of the principal Vadose Zone Media types. Range based upon
- a) Path length and tortuosity
- b) potential for dispersion and consequent dilution
- c) reactivity (solubility)
- d) consumptive sorption
- e) fracturing

Primary factors affecting rating
1. Consumptive sorption and fracturing
2. Fracturing and reactivity
3. Fracturing; path length as influenced by intergranular relationships
4. Fracturing; path length and tortuosity as influenced by bedding planes, sorption, and reactivity
5. Path length and tortuosity as impacted by bedding grain size, sorting and packing, sorption
6. Path length and tortuosity as influenced by grain size, sorting, and packing
7. Reactivity and fracturing

Figure 9. Graph of ranges and ratings for hydraulic conductivity.



provide units which are mappable and permit the drafting of pollution potential maps. Thus, the user can use hydrogeologic settings as a mappable unit, define the area of interest by modifying the ranges within a setting to reflect specific conditions within an area, choose corresponding ratings, and calculate a pollution potential DRASTIC Index or a specialized index for agricultural pesticides and herbicides.

References

Dee, Norbert, Janet Baker, Neil Drobny, Ken Duke, Ira Whitman, and Dave Fahringer, 1973. An environmental evaluation system for water resource planning; Water Resources Research, Vol. 9, No. 3, pp. 523-535.

Heath, Ralph C., 1984. Ground-water regions of the United States; U.S. Geological Survey Water Supply Paper 2242, 78 pp.

Section 3
DRASTIC: A Description of the Factors

Ground-Water Contamination and DRASTIC

Ground-water pollution is caused by a variety of substances originating from many different activities. In general, man-influenced contaminants enter ground water through three pathways: (1) the placing or spreading of liquids or water soluble products on the land surface, (2) the burial of substances in the ground above the water table, or (3) the emplacement or injection of materials in the ground below the water table (Lehr et al., 1976). Table 11 lists the activities which cause contamination through one or more of these pathways. A brief description of each of these activities is included in Appendix C, Sources of Ground-Water Contamination.

After release at the land surface, the contaminant may infiltrate downward through the soil, vadose zone, and saturated zone finally reaching the aquifer. If the volume of contaminant is not great, the contaminant may be flushed toward the water table by infiltrating precipitation or additional amounts of contaminant. Once within the aquifer, the contaminant may: (1) travel at the velocity of and in the direction of ground water (Figure 10), (2) travel slower than the ground water (Figure 11), (3) float on the surface of the water table (Figure 12), (4) "sink" through the aquifer to the bottom (Figure 13) or (5) under some conditions, may actually move in a direction against the flow of the ground water (Figure 14). Generally, the majority of contaminants travel in the direction of ground-water flow at a velocity somewhat less than that of the ground water.

Figure 10. Travel of contaminant with same density as water in the aquifer.

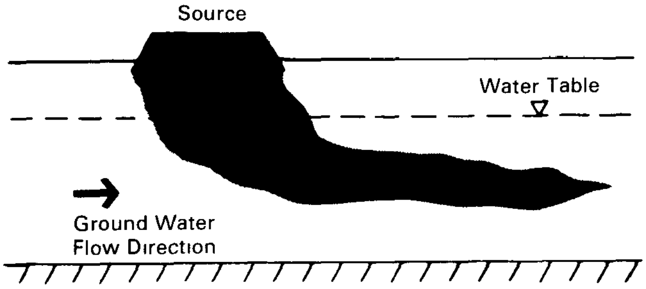
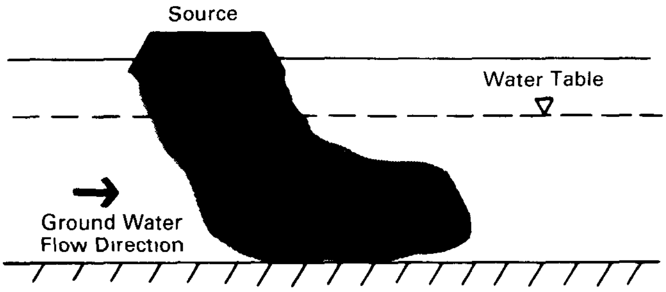


Figure 11. Travel of contaminant that is denser than water in the aquifer.



As the contaminant travels through this system, attenuation of the contaminant may take place. Attenuation includes those mechanisms which reduce the velocity of the contaminant through processes such as dilution, dispersion, mechanical filtration, volatilization, biological assimilation and decomposition, precipitation, sorption, ion exchange, oxidation-reduction, and buffering and neutralization (Pye and

Table 11. Potential Sources of Ground-Water Contamination and Mode of Emplacement (After Lehr et al., 1976)

On the Land Surface	In the Ground Above the Water Table	In the Ground Below the Water Table
1. Land disposal of either solid or liquid waste materials	1. Leaching tile fields, cesspools and privies	1. Waste disposal in wet excavations
2. Stockpiles	2. Holding ponds and lagoons	2. Drainage wells and canals
3. Disposal of sewage and water-treatment plant sludge	3. Sanitary landfills	3. Abandoned/improperly constructed wells
4. Salt spreading on roads, airport runways and parking lots	4. Waste disposal in excavations	4. Exploratory wells
5. Animal feed lots	5. Leakage from underground storage tanks	5. Water supply wells
6. Fertilizers and pesticides	6. Leakage from underground pipelines	6. Waste disposal wells
7. Accidental spills of hazardous materials	7. Artificial recharge	7. Mines
8. Particulate matter from airborne sources	8. Sumps and dry wells	8. Salt water intrusion
	9. Graveyards	

Figure 12. Travel of contaminant that is less dense than water in the aquifer.

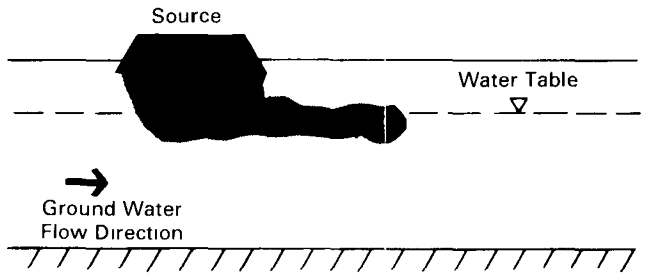


Figure 13. Travel of contaminant that is denser than water and sinks in the aquifer.

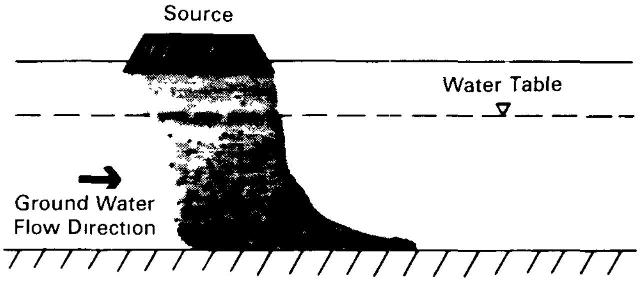
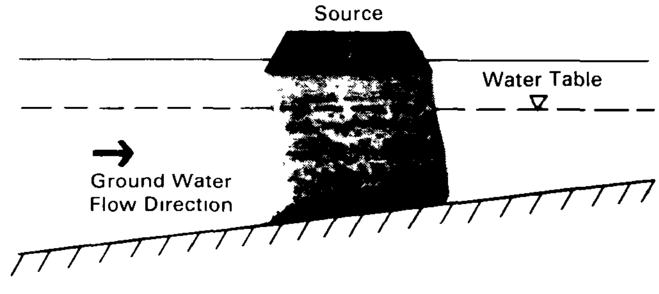


Figure 14. Travel of contaminant that is denser than water in the aquifer in a direction opposed to the water flow direction.



Kelley, 1984; Fetter, 1980). Dilution is accomplished by hydrodynamic dispersion. The degree of attenuation which can occur is a function of (1) the time that the contaminant is in contact with the material through which it passes, (2) the grain size and physical and chemical characteristics of the material through which it passes, and (3) the distance which the contaminant has traveled. In general, for any given material the longer the time and greater the distance, the greater the effects of attenuation. In a similar manner, the greater the surface area of the material through which the contaminant passes, the greater the potential for sorption of the contaminant and hence for attenuation. The greater the reactivity of the material through which the contaminant passes, the greater the potential for attenuation.

Any combination of these processes may be active depending on the hydrogeologic conditions and the contaminant. It is therefore necessary to have a general idea of these processes and whether they are active. A discussion of the mechanisms which control contaminant movement is included in Appendix A, Processes and Properties Affecting Contaminant Fate and Transport.

The effectiveness of dilution and attenuation processes is largely determined by (1) the rate and loading of the applied contaminant, (2) the characteristics of the contaminant, and (3) the physical characteristics of the area. Ultimately, it is these factors which control the ground-water pollution potential of any area. The rate and loading factor which generally is of site-specific character is discussed briefly in Section 5, IMPACT—Risk Factors. The characteristics of the contaminants are discussed in more detail in Appendix B, Characteristics of Ground-Water Contaminants. However, it is the physical properties characterized by the hydrogeologic setting of the area which determine the extent to which the attenuation mechanisms may have the potential to be active.

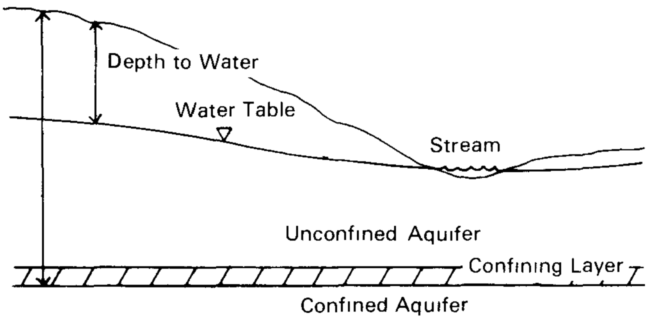
Because it is neither practical nor feasible to obtain quantitative evaluations of these intrinsic mechanisms from a regional perspective, it is necessary to look at the broader physical parameters which incorporate the many processes. Each of the DRASTIC parameters includes various mechanisms which will help to evaluate the vulnerability of ground water. A description of each DRASTIC feature and the included processes is contained in the following sections.

Depth to Water

The water table is the expression of the surface below the ground level where all the pore spaces are filled with water. Above the water table, the pore spaces are partially filled with water and air. The water table may be present in any type of media and may be either permanent or seasonal. For purposes of this document, depth to water refers either to the depth to the water surface in an unconfined aquifer or to the top of the aquifer where the aquifer is confined (Figure 15). Depth to water does not include saturated zones which have insufficient permeability to yield significant enough quantities of water to be considered an aquifer.

The depth to water is important primarily because it determines the depth of material through which a contaminant must travel before reaching the aquifer, and it may help to determine the amount of time during which contact with the surrounding media is

Figure 15. Depth to water in a confined and unconfined aquifer.



maintained. The depth to water is also important because it provides the maximum opportunity for oxidation by atmospheric oxygen. In general, there is a greater chance for attenuation to occur as the depth to water increases because deeper water levels infer longer travel times. Figure 3 shows the relative importance of depth to water. The ranges in depth to water as defined in the DRASTIC system have been determined based on what are considered to be depths where the significance for pollution potential changes.

Net Recharge

The primary source of ground water is precipitation which infiltrates through the surface of the ground and percolates to the water table. Net recharge indicates the amount of water per unit area of land which penetrates the ground surface and reaches the water table. This recharge water is thus available to transport a contaminant vertically to the water table and horizontally within the aquifer. In addition, the quantity of water available for dispersion and dilution in the vadose zone and in the saturated zone is controlled by this parameter. In areas where the aquifer is unconfined, recharge to the aquifer usually occurs more readily and the pollution potential is generally greater than in areas with confined aquifers. Confined aquifers are partially protected from contaminants introduced at the surface by layers of low permeability media which retard water movement to the confined aquifer. In some parts of some confined aquifers, head distribution is such that movement of water is through the confining bed from the confined aquifer into the unconfined aquifer. In this situation, there is little opportunity for local contamination of the confined aquifer. For a better understanding of how to deal with this situation, refer to the Section 4, How to Evaluate Confined Aquifers. The principal recharge area for the confined aquifer is often many miles away. Many confined aquifers are not truly confined and are partially recharged by migration of water through the confining layers. The more water that leaks through, the greater the potential for recharge to carry pollution into the aquifer. Recharge water, then, is a principal vehicle for leaching and transporting solid or liquid contaminants to the water table. Therefore, the greater the recharge, the greater the potential for pollution. This is true until the amount of recharge is great enough to cause dilution of the contaminant and the pollution potential ceases to increase and may actually decrease. For purposes of this document, this phenomena has been acknowledged but the ranges and associated ratings do not reflect the dilution factor.

One additional factor which must be considered is augmentation of natural recharge through artificial recharge or by irrigation. When a range for net recharge is assigned, these additional sources of water must be considered.

Aquifer Media

Aquifer media refers to the consolidated or unconsolidated medium which serves as an aquifer (such as sand and gravel or limestone). An aquifer is defined as a medium which will yield sufficient quantities of water for use. Water is held by aquifers in the pore spaces of granular and clastic rock and in the fractures and solution openings of non-clastic and non-granular rock. Rocks which yield water from pore spaces have primary porosity; rocks where the water is held in openings such as fractures and solution openings which were created after the rock was formed have secondary porosity. The aquifer medium exerts the major control over the route and path length which a contaminant must follow. The path length is an important control (along with hydraulic conductivity and gradient) in determining the time available for attenuation processes such as sorption, reactivity, and dispersion and also the amount of effective surface area of materials contacted in the aquifer. The route which a contaminant will take can be strongly influenced by fracturing or by any other feature such as an interconnected series of solution openings which may provide pathways for easier flow. In general, the larger the grain size and the more fractures or openings within the aquifer, the higher the permeability and the lower the attenuation capacity; consequently the greater the pollution potential.

For purposes of this document, aquifer media have been designated by descriptive names. Each medium is listed in the order of increasing pollution potential. A discussion of each medium follows:

(a) Massive Shale—Thick bedded shales, claystone or clays which typically yield only small quantities of water from fractures and which have a low pollution potential. Pollution potential is influenced by the degree of fracturing.

(b) Metamorphic/Igneous—Consolidated bedrock of metamorphic or igneous origin which contains little or no primary porosity and which yields water only from fractures within the rock. Typically well yields are low and the relative pollution potential is a function of the degree of fracturing.

(c) Weathered Metamorphic/Igneous—Unconsolidated material, commonly termed regolith or saprolite, which is derived by weathering of the underlying consolidated bedrock, and which contains primary porosity. The pollution potential is largely influenced by the amount of clay material present: the higher the clay content, the lower the pollution potential.

(d) Bedded Sandstone, Limestone, and Shale—Typically thin bedded sequences of sedimentary rocks which contain primary porosity but where the controlling factor in determining pollution potential is the degree of fracturing.

(e) Massive Sandstone—Consolidated sandstone bedrock which contains both primary and secondary porosity and is typified by thicker deposits than the Bedded Sandstone Limestone and Shale sequences. Pollution potential is largely controlled by both the degree of fracturing and the primary porosity of the sandstone.

(f) Massive Limestone—Consolidated limestone or dolomite bedrock which is characterized by thicker deposits than Bedded Sandstone, Limestone, and Shale sequences. Pollution potential is largely affected by the degree of fracturing and the amount of solution of the limestone.

(g) Sand and Gravel—Unconsolidated mixtures of sand- to gravel-sized particles which contain varying amounts of fine materials. Sands and/or gravels which have only small amounts of fine material are termed "clean." In general, the cleaner and more coarse-grained the aquifer, the greater the pollution potential.

(h) Basalt—Consolidated extrusive igneous bedrock which contains bedding planes, fractures, and vesicular porosity. The term is used herein in a generic sense, even though it is actually a rock type. Pollution potential is influenced by the amount of interconnected openings which are present in the lava flow materials.

(i) Karst Limestone—Consolidated limestone bedrock which has been dissolved to the point where large, open, interconnected cavities and fractures are present. This is a special case of Massive Limestone.

A graphic display of the ratings which have been assigned to each media is contained in Figure 5. This graph also contains a more complete listing of the mechanisms which affect the pollution potential of that media. Because this DRASTIC parameter is less quantifiable, the user will be instructed to choose a rating based on the above discussion and available information on the geology of the area (Section 4, How to Use the Range in Media Ratings).

Soil Media

Soil media refers to that uppermost portion of the vadose zone characterized by significant biological activity. For purposes of this document, soil is commonly considered the upper weathered zone of the earth which averages three feet or less. Soil has a significant impact on the amount of recharge which can infiltrate into the ground and hence on the ability of a contaminant to move vertically into the vadose zone. Moreover, where the soil zone is fairly thick, the attenuation processes of filtration, biodegradation, sorption, and volatilization may be quite significant. Thus, for certain on-land surface practices such as agricultural applications of pesticides or application of herbicides, soil can be a primary influence on pollution potential. In general, the pollution potential of a soil is largely affected by the type of clay present, the shrink/swell potential of that clay, and the grain size of the soil. In general, the less the clay shrinks and swells and the smaller the grain size, the less the pollution potential. The quantity of organic material present in the soil may also be an important factor. Soil media are best described by referring to the basic soil types as classified by the Soil Conservation Service. A description of the soil media in order of increasing pollution potential follows:

(a) Nonshrinking Clay—Illitic or Kaolinitic clays which do not expand and contract with the addition of water and therefore do not form vertical secondary permeability which increases the pollution potential.

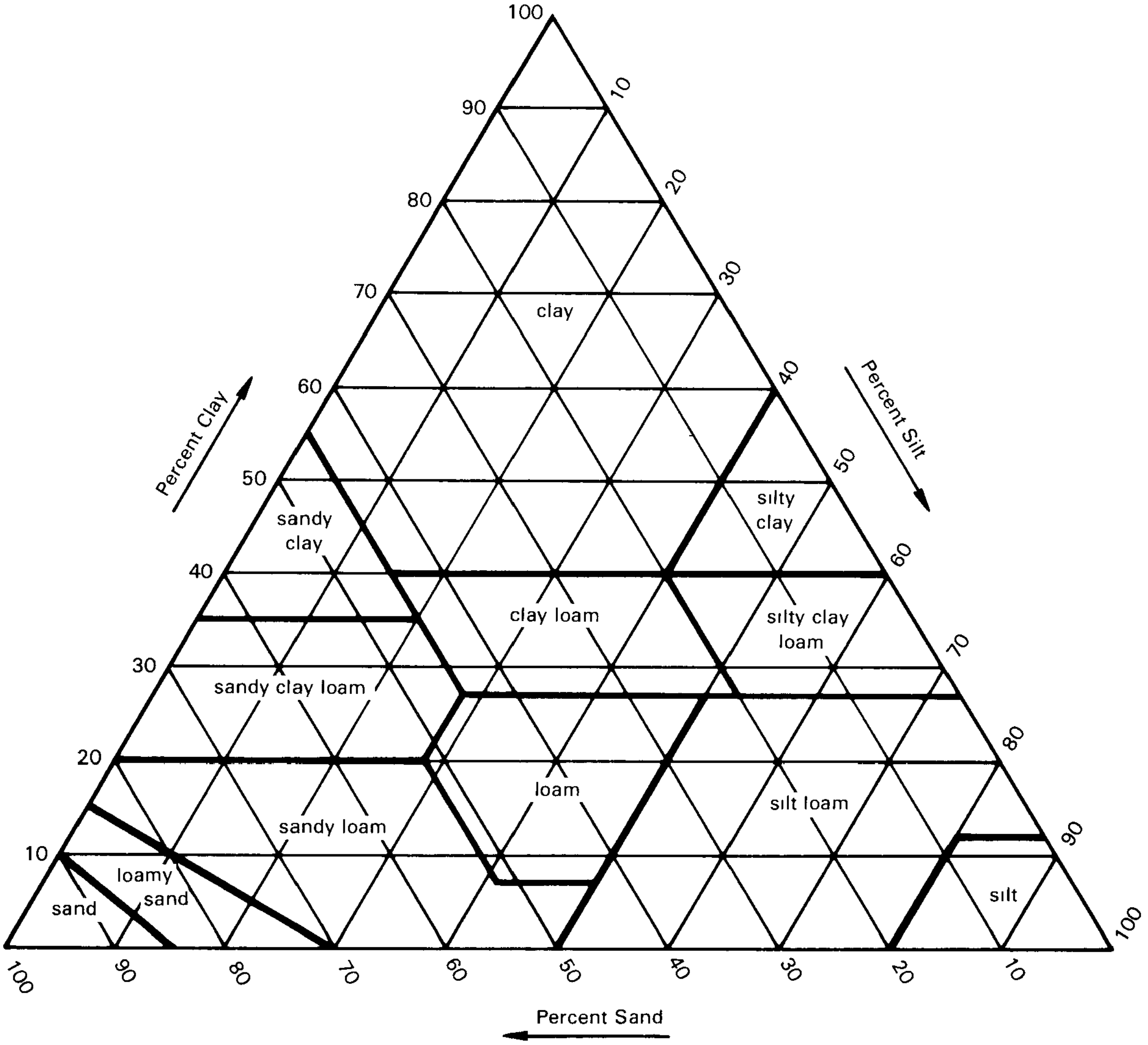
(b) Clay Loam—A soil textural classification which is characterized by 15-55 percent silt, 27-40 percent clay, and 20-45 percent sand (Figure 16). Because of the high amounts of clay and restrictive permeabilities, it has a low pollution potential.

(c) Silty Loam—A soil textural classification characterized by 50-85 percent silt, 12-27 percent clay, and 0-50 percent sand (Figure 16). The pollution potential is still low, but higher than a clay loam because of typically lower percentages of clay.

(d) Loam—A soil textural classification characterized by 25-50 percent silt, 7-27 percent clay, and 0-50 percent sand (Figure 16). The pollution potential is still low, but higher than a silt loam because of lower percentages of clay and silt.

(e) Sandy Loam—A soil textural classification characterized by 0-50 percent silt, 0-20 percent clay, and 15-50 percent sand (Figure 16). The pollu-

Figure 16. Soil textural classification chart (Soil Conservation Service, 1951).



tion potential is greater than a loam due to the higher percentage of sand.

(f) Shrinking Clay—Characterized by montmorillonitic clays or smectites which have an expanding lattice that swell and contract with alternating wetting and drying. Although the cracks formed on drying, swell as the clay hydrates, the ability of pollutants to move rapidly upon initial wetting is documented. Although usually of low permeability, this medium can have a seemingly high pollution potential based on the secondary vertical permeability created by the cracking of the media upon drying.

(g) Sand—A size-based delineation of angular or rounded particles ranging in size from 1/16 mm to 2 mm. Sands are typically free of silts and clays and therefore have a high pollution potential.

(h) Gravel—A particle-based size classification typified by particles larger than 2 mm in size and commonly a mixture of sand, silt, clay, and gravel with a preponderance of large-sized particles. Permeability is rapid and pollution potential is high.

(i) Thin or Absent—If a soil layer is not present or if the layer is so thin as to be considered ineffective, the pollution potential is very high and this category should be used. Figure 6 contains a graphic representation of the pollution potential of soil media.

Topography

As used here, "topography" refers to the slope and slope variability of the land surface. Basically, topography helps control the likelihood that a pollutant will run off or remain on the surface in one area long enough to infiltrate. This is particularly important in activities such as application of pesticides and herbicides where the effect of the contaminant tends to be cumulative. Therefore, the greater the chance of infiltration, the higher the pollution potential associated with the slope. Topography influences soil development and therefore has an effect on attenuation. Topography is also significant from the standpoint that the gradient and direction of flow often can be inferred for water table conditions from the general slope of the land. Typically, steeper slopes signify higher ground-water velocity.

Figure 7 contains the ranges which were chosen as significant for pollution potential. These ranges correspond to the ranges identified by the Soil Conservation Service for percent slope. The ranges are assigned ratings assuming that 0-2 percent slope provides the greatest opportunity for a pollutant to infiltrate because neither the pollutant nor much precipitation exits the area as runoff. Conversely, 18+ percent slope affords a high runoff capacity and therefore a lesser probability of infiltration with subsequent lower pollution potential. However, steep slopes are more conducive to rapid erosion and contamination of surface water.

Impact of Vadose Zone

The vadose zone is defined as that zone above the water table which is unsaturated. For purposes of this document, this strict definition can be applied to all water table aquifers. However, when evaluating a confined aquifer, the "impact" of the vadose zone is expanded to include both the vadose zone and any saturated zones which overlie the aquifer. The significantly restrictive zone above the aquifer which forms the confining layer is used as the type of media which has the most significant impact.

The type of vadose zone media determines the attenuation characteristics of the material below the typical soil horizon and above the water table. Biodegradation, neutralization, mechanical filtration, chemical reaction, volatilization, and dispersion are all processes which may occur within the vadose zone with a general lessening of biodegradation and volatilization with depth. The media also control the path length and routing, thus affecting the time available for attenuation and the quantity of material encountered. The routing is strongly influenced by any fracturing present. The materials at the top of the vadose zone also exert an influence on soil development.

Vadose zone media have been designated by descriptive names. Each medium, listed in order of increasing pollution potential, is discussed as follows:

(a) Silt/Clay—A deposit of silt- and clay-sized particles which serves as a barrier to retard movement of liquids. The high clay content provides a low pollution potential. Shrinking clays and higher silt concentrations increase the pollution potential.

(b) Shale—A consolidated, thick-bedded clay rock which may be fractured. Pollution potential is low but increases with the degree of fracturing.

(c) Limestone—Consolidated massive limestone or dolomite which typically contains fewer bedding planes than Bedded Limestone, Sandstone, and Shale sequences (see "e" below). Pollution potential is influenced by the degree of fracturing, with a high density of fracturing increases the chance for pollutant migration.

(d) Sandstone—A consolidated sand rock which contains both primary and secondary porosity and is typified by thicker bedding than compared to Bedded Limestone, Sandstone, Shale sequences. Pollution potential is largely controlled by the degree of fracturing and the primary porosity of the sandstone.

(e) Bedded Limestone, Sandstone, Shale—Typically thin-bedded sequences of sedimentary rocks which contain primary porosity but where the controlling factor in determining pollution potential is the degree of fracturing.

(f) Sand and Gravel with Significant Silt and Clay—Unconsolidated mixtures of sand and gravel which contain an appreciable amount of fine material affect pollution potential by having a high concentration of clay or by reducing the permeability of the deposit. These deposits are commonly referred to as "dirty" and have a lower pollution potential than "clean" sands and gravels. In general, finer-grained and "dirtier" sands have a lower pollution potential than coarser-grained "dirtier" gravels.

(g) Metamorphic/Igneous—Consolidated rock of metamorphic or igneous origin which contain no significant primary porosity and which permit movement of liquids through fractures. The relative pollution potential is a function of the degree of fracturing.

(h) Sand and Gravel—Unconsolidated mixtures of sand- to gravel-sized particles which contain only small amounts of fine materials. The range in rating reflects principally a grain size distribution where unsorted smaller grained deposits have a lower pollution potential and larger grained, well-sorted deposits have a higher pollution potential.

(i) Basalt—Consolidated extrusive igneous bedrock which contains bedding planes, fractures, and vesicular porosity. This is a special case of Metamorphic/Igneous. The term is used herein in a generic sense, even though it is actually a rock type. Pollution potential is influenced by the number and amount of interconnected openings present in the lava flow materials. Pollution potential is typically high because there is little chance for attenuation once a pollutant enters the fracture system.

(j) Karst Limestone—Consolidated limestone bedrock which has been dissolved to the point where large open interconnected cavities and fractures are present. This is a special case of Limestone, where pollution potential is high based on the amount of open area in the rock.

A graphic display of the ratings which have been assigned to each medium is contained in Figure 8. This graph also contains a more complete listing of the mechanisms which affect the pollution potential of that media. Because this DRASTIC parameter is less quantifiable, the user is instructed to choose a rating based on the above discussion and available information on the geology of the area (Section 4, How to Use the Range in Media Ranges).

Hydraulic Conductivity of the Aquifer

Hydraulic conductivity refers to the ability of the aquifer materials to transmit water, which in turn, controls the rate at which ground water will flow under a given hydraulic gradient. The rate at which the ground water flows also controls the rate at which a contaminant will be moved away from the point at which it enters the aquifer. Hydraulic conductivity is controlled by the amount and interconnection of void spaces within the aquifer which may occur as a consequence of intergranular porosity, fracturing, bedding planes, etc. For purposes of this document, hydraulic conductivity is divided into ranges where high hydraulic conductivities are associated with higher pollution potential. This is because the pollutant has the potential for moving quickly away from the point in the aquifer where it is introduced. Obviously, a wide range of hydraulic conductivities are present in all areas. The values assigned are considered to be typical for the settings described. Figure 9 shows the relative importance of the ranges.

Interaction Between Parameters

From the above discussion and in the application of the DRASTIC Index, it will be recognized that there is apparent redundance between some of the parameters. The depth to the water, for example, affects the quantity of material that will be encountered by a pollutant moving downward toward an aquifer. The thicker the section in a given setting, the greater the effect may be upon the degradation, retardation, or attenuation of the pollutant.

However, in considering the impact of the vadose zone, degradation, retardation, and other significant attenuation processes are all varied according to the nature of the materials present, and their condition within the vadose zone. If, for instance, the vadose zone is moderately fractured granite, the materials within the vadose zone will have only a slight impact on most pollutants entering the vadose zone. The protection provided will be a function of depth and the failure of critical fractures to interconnect.

If, however, the vadose zone is comprised of unfractured glacial till (silt/clay), it can be anticipated that consumptive sorption will be moderately high; infiltration will be moderately low; retardation will be significant; and with any substantial thickness of till, considerable time will be required for most (conservative) pollutants to penetrate the till. Thus it can be seen that the redundant consideration of degradation, retardation, and attenuation within the context of both depth to water and impact of the vadose zone is useful in the comparative evaluation of sites.

Net recharge determines, on an annual basis, the quantity of water from precipitation that is available for vertical transport, dispersion, and dilution of a pollutant from a specific point of application. Net recharge exemplifies how some parameters can have both positive and negative effects. For example, greater recharge typically means more rapid transport of a pollutant and therefore less time for attenuation. However, in this situation, dilution is also greater thereby exerting a positive influence because the concentration of an introduced contaminant will be lessened. It is also evident that a thick unsaturated zone, with a layered sequence of a bedded and fractured shales, sandstones, and limestones, can have a profound impact on all three of the same factors (transport, dispersion, dilution) that are of primary importance to net recharge.

Topography and soil media also influence net recharge. Topography has site-specific influence which determines whether the capacity for recharge is high or low at a given point. The permeability of the surface soils has a similar impact. However, the nature of the surface soil materials has an additional impact upon potential pollutant attenuation, consumptive sorption, route length and direction, and time available for penetration.

In addition to its direct influence upon recharge, topography exerts a significant influence upon soil thickness, drainage characteristics, and profile development. These factors, in turn, influence soil media as well as the previously-mentioned factors. In addition, topography usually bears a predictable relationship to hydraulic gradient, and direction of probable pollutant movement under water table conditions, with a consequent impact on dispersion and dilution.

The upper portion of the vadose zone exerts influence on the type of soils developed on the surface. The vulnerability of an aquifer to a given pollution event varies in response to the nature of the materials in the vadose zone; grain size, sorting, reactivity, bedding, fracturing, thickness, sorptive character. In general, finer grain-size materials, i.e. clays and silt, have lower hydraulic conductivity, greater capacity for the temporary and long-term attenuation of pollutants, and greater sorptive capacity. If expandable clay minerals are present, the sorptive capacity is further enhanced. If a material is even moderately cemented, then grain size and sorting may be less significant than the degree of cementation.

If the material in the vadose zone is reactive to the pollutant, or soluble in it, then there may be two different effects. First, the pollutant may be retarded (a positive effect) or second, the solution of the vadose zone material may actually increase permeability and allow subsequent introduction of pollutants to pass through more quickly with less retardation (a negative effect). In the case of reactive pollutants, the importance of secondary by-products must be considered. It is here that the risks associated with gaseous phase transport are most likely to have an impact on ground water.

The thickness of the vadose zone and the degree of fracturing and frequency of bedding planes in it all impact upon the tortuosity, route length, dispersion, and consequent travel time that is required for a pollutant to move through the vadose zone. This is not only of time-delay importance but is important as the control of contact time for reactions to occur.

The vadose zone, including the surficial soil, is also of great importance as the zone where most of the biologic activity occurs. There are natural organisms found in this zone that break down many polluting substances into secondary by-products, both harmless and harmful. For many chemicals these reactions are very poorly understood, if at all, but it is known that with sufficient time the eventual results are generally beneficial. Among the best known of these processes at present are the bacterial fixation of iron and the bacterial breakdown of non-chlorinated hydrocarbons under natural conditions. Both of these processes occur in the vadose zone and in the aerobic portion of shallow aquifers.

The hydraulic conductivity, together with gradient and porosity of the aquifer beneath a site, influences the rate of movement of an introduced pollutant away from the point of introduction. In conjunction with hydraulic gradient, conductivity also controls the direction of movement. These are, in turn, affected with regard to dispersion, by grain size, bedding, fracturing, and tortuosity.

It is evident that all of the DRASTIC parameters are interacting, dependent variables. Their selection is based not on available data quantitatively developed and rigorously applied, but on a subjective understanding of "real world" conditions at a given area. The value of the DRASTIC parameters is in the fact that they are based on information that is readily available for most portions of the United States, and which can be obtained and meaningfully mapped in a minimum of time and at minimum cost. The DRASTIC ranking scheme can then be applied by enlightened laymen for valid comparative evaluations with acceptable results.

If the vulnerability of a site, or sites, to pollution were to be evaluated with regard to travel time, flux, and concentration associated with the incidence of a pollutant introduced at the site, the DRASTIC parameters would be distributed as follows:

A. Travel Time
   - Depth to Water
   - Soil Media
   - Impact of Vadose Zone
   - Net Recharge
   - Conductivity

B. Flux
   - Aquifer Media
   - Conductivity (Existence of Gradient Assumed)

C. Concentration
   - Depth to Water
   - Net Recharge
   - Aquifer Media
   - Soil Media
   - Topography
   - Impact of Vadose Zone
   - Conductivity

It should be noted that although the DRASTIC parameter of hydraulic conductivity of the aquifer is mapped as a function of the ability of a pollutant to be moved from a point of incidence, the direction of migration is a function of gradient and rate depends on both conductivity and gradient.

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Section 4
How to Use Hydrogeologic Settings and DRASTIC

The system described in this document presents a simple and easy-to-use approach to assess the ground-water pollution potential of any area. Although the final system appears simplistic, the system actually includes many complex concepts and relationships. Before an attempt is made to make full use of this system, the user needs to develop an appreciation for the complexity of evaluating ground-water pollution potential. It is not necessary to understand every concept in detail, but the greater the depth of understanding, the more useful the system becomes. DRASTIC provides mappable results which can be used to provide a quick reference of relative pollution potential of different areas. DRASTIC is designed to be used as a planning or screening tool. DRASTIC and associated maps cannot be used in site-specific evaluations because of local complexities in geologic conditions.

Organization of the Document

As described in Section 2, Development of the System and Overview, the entire United States has been divided into 13 geographic regions and each region subdivided into hydrogeologic settings. Section 6, Hydrogeologic Settings of the United States by Ground-Water Regions, contains an annotated description of each region, a geographic location map for each region, and an illustration of the major hydrogeologic features of the region. Each hydrogeologic setting contains a written narrative, an illustration, and two DRASTIC charts. These charts contain a listing of the seven DRASTIC features, an example of typical ranges for each feature which might be encountered in the region, a listing of the weight which has been assigned to the DRASTIC feature, a rating which corresponds to the associated range (from Tables 4-10), a column which reflects the weight multiplied by the rating for each factor, and a total DRASTIC Index. The same information is contained in the second agricultural DRASTIC chart. The significant difference between the charts is in the weights assigned to each DRASTIC feature, thus yielding a separate specialized agricultural DRASTIC Index.

Table 18 contains a complete listing of all hydrogeologic settings and their associated DRASTIC Index. Table 19 arranges the hydrogeologic settings by increasing DRASTIC Index values. Table 20 arranges the hydrogeologic settings alphabetically so that comparison of similar settings in different regions can be accomplished. Tables 21-23 contain the same information computed for the modified agricultural DRASTIC Index. These lists have been prepared to assist the user in evaluating the relative pollution potential for many hydrogeologic settings. Following these listings are Tables 24 and 25 which provide a summary of principal physical and hydrologic characteristics and common ranges of the hydraulic characteristics of the ground-water regions as defined by Heath (1984). These values may assist the user in evaluating hydrogeologic settings.

The other important information necessary to use DRASTIC is contained in the ranges and rating tables for each factor. For ease of reference, Tables 4-10 have been reprinted in Section 6 as Tables 26-32. This set of tables consists of a complete listing of the DRASTIC factors, the ranges and associated rating for each factor, and the weights for both the DRASTIC and modified agricultural DRASTIC system.

Where to Obtain Information on DRASTIC Parameters

Before an area can be evaluated using the DRASTIC system, the basic information on each factor must be found. DRASTIC has been designed to use information which is available from a variety of sources. Table 1 contains a listing of possible sources of hydrogeologic information and the types of information which may be available from each. The most common source of information for each parameter is listed below:

(1) Depth to Water—Well logs or hydrogeologic reports;
(2) Net Recharge—Water resource reports combined with data on precipitation from the National Weather Service;
(3) Aquifer Media—published geologic and hydrogeologic reports;
(4) Soil Media—published soil survey reports or local mapping projects conducted by the Soil Conservation Service;

(5) Topography—published U.S. Geological Survey topographic maps (various scales);
(6) Impact of the Vadose Zone—published geologic reports;
(7) Hydraulic Conductivity of the Aquifer—published hydrogeologic reports. (Of all the factors, this information may be the most difficult to find. Because it is related very closely to aquifer media, if necessary, hydraulic conductivity may be estimated using Table 12). Conversion factors for permeability and hydraulic conductivity are found in Table 13.

It should be noted that the more accurate the data used to compute the index, the more reliably the pollution potential can be assessed. There may be many gaps in the data, of course. These gaps can be filled with careful interpolation if such interpolation is reasonable.

Steps for Use of the System

In order to use the DRASTIC system, the user must follow a few simple steps. The following example illustrates how to use the system. A decision-maker wishes to evaluate the pollution potential of two areas in a county. The county is located along the glacial boundary such that part of the county lies in the Glaciated Central Region and the other part lies in the Non-Glaciated Central Region. Precipitation in the area averages 42 inches per year. Area I is typified by 5 to 20 feet of glacial till deposits, which overlie fractured sandstones and shales with hydraulic conductivities ranging from 100 to 300 gpd/ft^2. The terrain is rolling, and depth to the water in the sandstones averages 30 feet below land surface. Typical soils have mixtures of sand, silt, and clay with predominant clay fractions. Area II is typified by alternating sequences of sandstone, limestone, and

Table 12. Range of values of hydraulic conductivity and permeability (Freeze and Cherry, 1979)

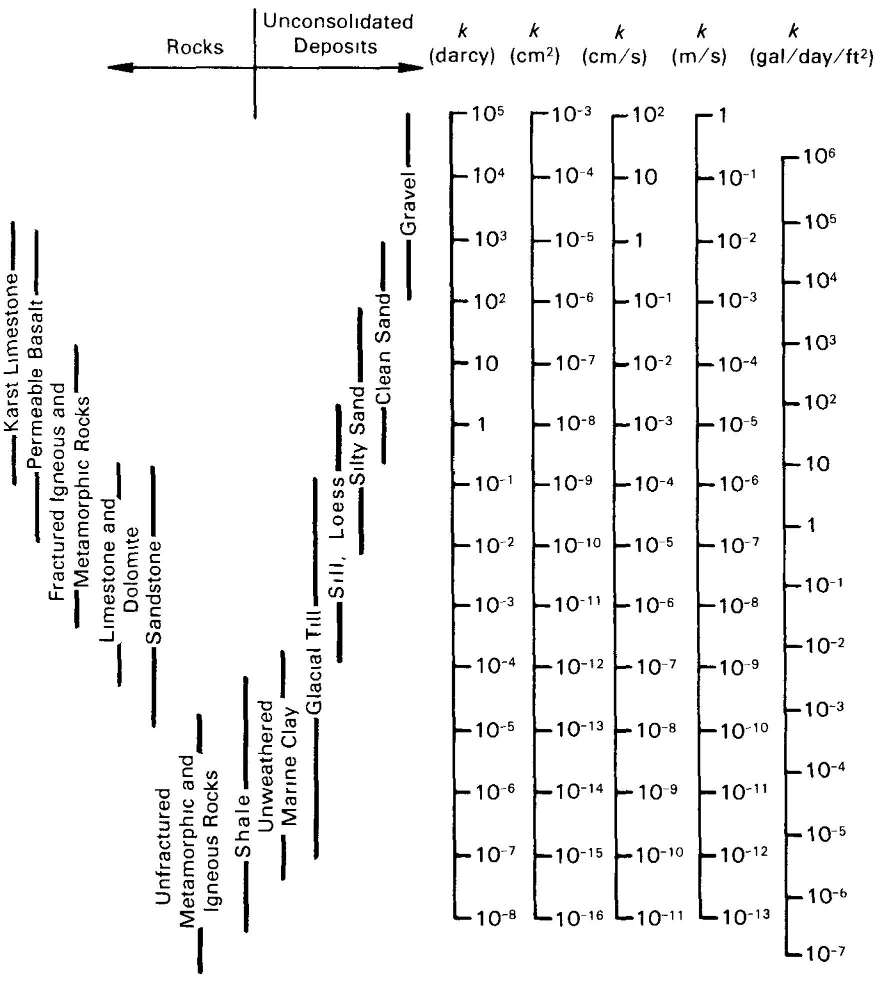


Table 13. **Conversion Factors for Permeability and Hydraulic Conductivity Units (Freeze and Cherry, 1979)**

	Permeability, k*			Hydraulic conductivity, K		
	cm^2	ft^2	darcy	m/s	ft/s	U.S. gal/day/ft^2
cm^2	1	1.08×10^{-3}	1.01×10^{8}	9.80×10^{2}	3.22×10^{3}	1.85×10^{9}
ft^2	9.29×10^{2}	1	9.42×10^{10}	9.11×10^{5}	2.99×10^{6}	1.71×10^{12}
darcy	9.87×10^{-9}	1.06×10^{-11}	1	9.66×10^{-6}	3.17×10^{-5}	1.82×10^{1}
m/s	1.02×10^{-3}	1.10×10^{-6}	1.04×10^{5}	1	3.28	2.12×10^{6}
ft/s	3.11×10^{-4}	3.35×10^{-7}	3.15×10^{4}	3.05×10^{-1}	1	6.46×10^{5}
U.S. gal/day/ft^2	5.42×10^{-10}	5.83×10^{-13}	5.49×10^{-7}	4.72×10^{-7}	1.55×10^{-6}	1

*To obtain k in ft^2, multiply k in cm^2 by 1.08×10^{-3}

shale with moderate fracturing and hydraulic conductivity averaging 300 gpd/ft^2. Relief is low and slopes are commonly 2 percent. Depth to water averages 40 feet. Soil is thin but significant with soils reflecting equal mixtures of sand, silt, and clay. Average net recharge is 8 inches per year.

(1) Identify the Region in which the area is located. Become familiar with the hydrogeology of the region. Area I is in the Glaciated Central Region and Area II is in the Non-Glaciated Central Region.

(2) Identify which hydrogeologic setting most closely approximates the conditions of the area. Area I most closely approximates Setting 7Aa—Glacial Till Over Bedded Sedimentary Rocks; Area II, 6Da—Alternating Sandstone, Limestone and Shale—Thin Soil. For ease of reference, these setting descriptions are included as Figures 17 and 18 and Tables 14 and 15.

(3) Evaluate available area information for each DRASTIC parameter against the ranges chosen for each DRASTIC parameter listed in the top table (Tables 14 and 15). In Area I (Table 14), the depth to water averages 30 feet; the assigned range of 30-50 would seem appropriate. Therefore, the associated rating of 5 (Table 4) does not need to be changed. No value for Net Recharge was available; however, precipitation in the region is 42 inches per year and recharge will typically be restricted due to the presence of clayey till; the assigned range of 4-7 seems appropriate. Therefore, the associated rating of 6 (Table 5) does not need to be changed. The aquifer media are fractured sandstones and shales; thin bedded sandstone, limestone, and shale sequences are present, so this is appropriate. Therefore, the associated rating of 6 (Table 6) does not need to be changed. Soils have a predominant clay fraction but contain silt and sand; clay loam is the prevalent soil, so the chart designation would be appropriate. Therefore, the associated rating of 3 (Table 7) does not need to be changed. Terrain is rolling; 2-6 percent slopes are predominant. The listed range is acceptable. Therefore, the associated rating of 9 (Table 8) does not need to be changed. The vadose zone is comprised of glacial till; silt and clay is the most significant portion of the

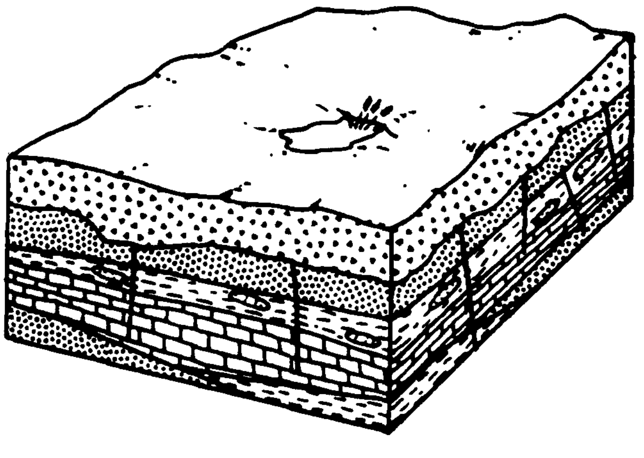


Figure 17. Description and illustration for setting 7 Aa—glacial till over bedded sedimentary rocks.

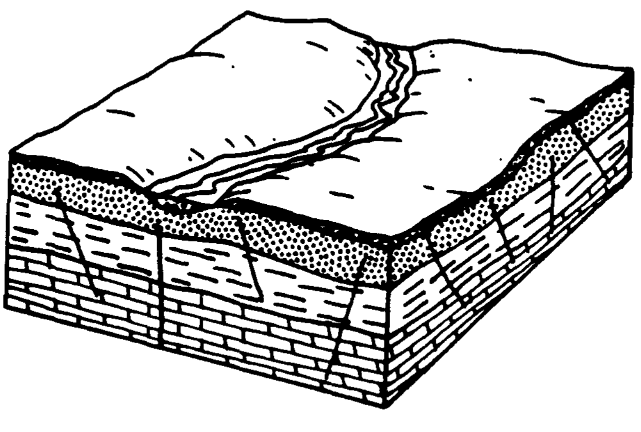


Figure 18. Description and illustration for setting 6Da—alternating sandstone, limestone and shale-thin soil.

Table 14. DRASTIC and Agricultural DRASTIC Charts for for Setting 7Aa—Glacial Till Over Bedded Sedimentary Rocks

Setting 7Aa Glacial Till Over Bedded Sedimentary Rock — General

Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	4-7	4	6	24
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Clay Loam	2	3	6
Topography	2-6%	1	9	9
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	100-300	3	2	6
		DRASTIC Index		93

Setting 7Aa Glacial Till Over Bedded Sedimentary Rock — Agricultural

Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	4-7	4	6	24
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Clay Loam	5	3	15
Topography	2-6%	3	9	27
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	100-300	2	2	4
		Agricultural DRASTIC Index		117

Table 15. DRASTIC and Agricultural DRASTIC Charts for Setting 6Da—Alternating Sandstone, Limestone and Shale-Thin Soil

Setting 6Da Alternating SS, LS, SH-Thin Soil — General

Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Loam	2	5	10
Topography	2-6%	1	9	9
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	1-100	3	1	3
		DRASTIC Index		129

Setting 6Da Alternating SS, LS, SH-Thin Soil — Agricultural

Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Loam	5	5	25
Topography	2-6%	3	9	27
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	1-100	2	1	2
		Agricultural DRASTIC Index		155

glacial till and is appropriate. Therefore, the associated rating of 1 (Table 9) does not need to be changed. Hydraulic conductivity values for the bedrock range from 100-300 gpd/ft^2 as listed on the chart. Therefore, the associated rating of 2 (Table 10) does not need to be changed. Since all the ranges in the hydrogeologic setting are acceptable, no values need to be modified for this area. The DRASTIC Index has already been computed for the user by multiplying each rating by the assigned weight to obtain the value listed in the "number" column. The sum of the "numbers" is the DRASTIC Index. In this instance, the DRASTIC Index of 93 is simply read from the chart. It should be noted here that weights are never changed. These were determined by the committee and are the essence of the system.

In Area II (Table 15), depth to water averages 40 feet. The range on the chart indicates 10-30 feet. This range is not acceptable. The user should refer to Table 4 to find the correct range which most closely approximates the area. In this case, 30-50 would be appropriate. Note the corresponding rating would now be 5 instead of 7 and the resultant weight of 5 multiplied by a rating of 5 is 25 instead of 35. Net recharge is 8 inches per year; 4-7 is an acceptable range and the associated rating of 6 does not need to be changed. The aquifer is alternating sequences of shale with moderate fracturing; the media listed on the chart is accurate and the associated rating of 6 does not need to be changed. Soils are typified by equal mixtures of sand, silt, and clay; this is the definition of loam, so the range is adequate and the associated rating of 5 does not need to be changed. Topography is low (2 percent slope); the range is listed as 2-6 percent. The user may, based on observation, choose 0-2 percent, and change the rating as before, or may accept the range of 2-6 if correct. For demonstration purposes, the user can refer to Table 8, choose a 0-2 percent range, change the rating from

9 to 10, and multiply by the weight of 1 to obtain an answer of 10 instead of 9. The vadose zone media are fractured limestones, sandstones, and shales; this is acceptable. Therefore, the associated rating of 6 does not need to be changed. Hydraulic conductivity averages 300 gpd/ft^2; the range indicates 1-100 gpd/ft^2. Refer to Table 10 to choose the appropriate range. In this case, 100-300 gpd/ft^2 is chosen, the associated rating of 2 is substituted and multiplied by 3 to obtain 6. The DRASTIC Index cannot be read off the chart because not all the ranges were appropriate for the setting. Calculate the correct DRASTIC Index by adding the numbers 25 + 32 + 18 + 10 + 10 + 30 + 6 = 131. The decision maker can then compare the two areas relative to one another.

From the above discussion, it is evident that the hydrogeologic settings serve as a guide to the user in evaluating the appropriate range for each DRASTIC factor. Each range has an associated rating which can then be integrated into DRASTIC by combining it with the weighting factor. The information to evaluate each DRASTIC factor and choose the appropriate range may not always be expressed in exactly the same terms which are used in this document. Section 3, DRASTIC: A Description of the Factors, contains a brief description of what is included in each of the media terms so that the most accurate DRASTIC range can be chosen.

How to Use the Range in Media Ratings

Because geologic media are more highly variable than many of the quantifiable DRASTIC factors, the associated rating for each of the ranges is a number which can vary within the rating indicated on the chart. For example, Table 6 contains the rating for aquifer media. Basalt has a rating which can vary from 2-8. By referring to Section 3, Aquifer Media, Impact of the Vadose Zone, which contains a description of the variables which affect the rating, the user may choose an appropriate rating for the area being evaluated. For example, the basalts in the Columbia Lava Plateau are extremely variable in the degree of interconnection of openings. In one area, the openings may be highly connected and be assigned a rating of 10. If data indicated a moderate degree of interconnection, a rating of 7 might be chosen. In this way the user can more closely approximate the actual conditions in the area. For purposes of the hydrogeologic settings, a typical rating is assigned to each of the ranges. The user has the option of using this typical rating where applicable.

How to Evaluate Confined Aquifers

Confined aquifers are treated, in the DRASTIC Index, by evaluating the relative importance of their confinement. Although the confined aquifer may have either an upward or downward leakage component, hydraulic gradients which result in upward flow are not taken into consideration because (a) the aquifer already has a degree of protection and (b) upward gradients are easily reversed by local pumpage. Therefore, for purposes of the DRASTIC Index, the worst case scenario of a gradient into the aquifer is always assumed. A judgement must be made in several of the DRASTIC factors as to the proper way to evaluate that factor in the specific setting. Factors that must be varied and the guidance for making the judgement of variation are as follows:

Depth to Water—This factor can be evaluated as either the depth to the water surface in an unconfined aquifer, or as the depth to the top of the aquifer where the aquifer is confined.

Net Recharge—varies with the degree of confinement.

Aquifer Media—no change in judgement calls.

Soil Media—varies with the degree of confinement, but is less sensitive than Net Recharge. When there is significant confinement, this rating is not read off the chart but is assigned a value of 1.

Topography—similar in impact to Soil Media, except that the relationship is inverse. When there is significant confinement, this rating is not read off the chart but is assigned a value of 1.

Impact of Vadose Zone—Since the "impact" of the vadose zone is now, in effect, considered as a functional aquitard, this zone is treated as a Silt/Clay media, and is assigned the associated chart rating of 1.

Hydraulic Conductivity—no change in judgement.

From this discussion it can be seen that the vulnerability of a specific aquifer to pollution varies with its degree of confinement, but that the comparative vulnerability of two protected aquifers is a function of their ability to disperse a pollutant from the point of application. To illustrate this, compare setting 7Ac, Glacial Till Over Solution Limestone, with setting 10Aa, Unconsolidated and Semi-Consolidated Regional Aquifers (Section 6). Setting 7Ac is typified by conditions in northeastern Indiana, and Setting 10Aa is typified by the Tidewater area in Virginia. Both aquifers are confined. In the first example (7Ac), piezometric levels rise above the carbonate aquifer and saturate the lower portion of the surficial till. The most important depth is the depth to the top of the saturated zone. In spite of the confinement, average recharge over the area is relatively high. Soil media and topography are still significant, even though it could be argued that their importance should be somewhat reduced. This would give the setting a lower rating.

In the second example, setting 10Aa, the deep aquifers are clearly confined by an overlying aquitard that separates the shallow water table aquifer (setting 10Ab) from the deeper zone. While the shallow aquifer provides recharge to the deeper, the rate of leakage is very, very low. Under this circumstance the Depth to Water is interpreted to be the depth to the top of the principal aquifer being considered. Net recharge to the deeper zone is almost negligible. Soil media has no real significance, nor does topography, so both ratings are reduced to a minimum value, or 1. The "impact" of the vadose zone is considered an effective aquitard, and is therefore rated as a silt/clay, or 1, regardless of its actual composition.

From a comparison of the two ratings, 129 (Setting 7Ac) versus 53 (Setting 10Aa), it is apparent that the deeper, highly confined, coastal aquifer is much more protected than the shallow, partially-confined aquifer. The deep coastal aquifers are actually only highly vulnerable to injected pollutants and widespread pollution of the overlying shallow aquifer, from which recharge is derived over a substantial period of time. Thus, in all DRASTIC settings the total hydraulic condition must be considered in order to evaluate the degree of protection provided to the aquifer being considered.

Single Factor Overrides

In some instances, it will be found that the DRASTIC Index cannot adquately compensate for a single parameter that is so dominant that it overrides all other parameters. This may be a consideration that is glaringly apparent, as in a highly-fractured surficial karst area, as is evident in parts of Florida, Indiana, or Kentucky; or, it may be a much more subtle consideration that involves design decisions and perhaps policy decisions.

Tables 16 and 17 provide the DRASTIC ratings for two actual sites, referenced as Maco I and Maco II. These sites are both located in the till plains portion of the Glaciated Central Region about five miles apart. Based on the available data, both sites are underlain by 25 to 40 feet of dense till containing a few discontinuous lenses of dirty sand and gravel that rarely exceed four inches in thickness. In the absence of fracturing or stratification, the horizontal and vertical permeabilities of the tills tend to fall in the 10^{-6} to 10^{-7} gpd/ft^2 range.

At site Maco I, the till overlies fractured limestone which serves as a regional aquifer and has a hydraulic conductivity usually in the 300-700 gpd/ft^2 range. Water in the limestone is confined, with the regional piezometric surface at about 30 feet. The overlying till is saturated only in association with the occasional discontinuous lense of sand and gravel. These zones can be considered "perched."

Table 16. DRASTIC Rating for MACO I

MACO I		General		
Feature	Range	Weight	Rating	Number
Depth to Water	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Massive Limestone	3	4	12
Soil Media	Clay Loam	2	3	6
Topography	2-6%	1	9	9
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	300-700	3	4	12
		DRASTIC Index		103

Table 17. DRASTIC Rating for MACO II

MACO II		General		
Feature	Range	Weight	Rating	Number
Depth to Water	5-15	5	9	45
Net Recharge	4-7	4	6	24
Aquifer Media	Massive Shale	3	2	6
Soil Media	Clay Loam	2	3	6
Topography	2-6%	1	9	9
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	1-100	3	1	3
		DRASTIC Index		98

At the Maco II site, the till overlies dense, fractured shale. The hydraulic conductivities of the shale are less than 1 gpd/ft^2. As a consequence of the relative impermeability of the shale bedrock, the overlying till is saturated from the depth of about five feet, even though the elevation, topography, and soils are similar at the two sties.

It can be seen by comparing Tables 16 and 17 that Maco II has a slightly more favorable rating than Maco I. The principal reason is because there is no significant aquifer at risk at site Maco II. However, site Maco II has a "water table," albeit a saturated till at a depth of five feet. At site Maco I a landfill, for example, could be properly designed and operated at a maximum depth of 15 feet and be well within the unsaturated zone, with a substantial thickness of dense, low permeability material at the base to protect the regional aquifer. Construction of a landfill at Maco II (with the more favorable rating) involves operating a saturation zone landfill, which often requires a serious policy decision from the permitting agency.

With regard to the proper application of the DRASTIC Index to this situation, the question is "Is the shallow, five-foot depth to saturation of sufficient significance to 'override' all of the other favorable aspects of the site." This should be considered for all parameters that are very highly-rated, i.e., in the rating range of 8-10.

Another single factor override would be exposed, highly-fractured or dissolved bedrock which would provide a direct conduit to an aquifer. Knowledge of the area being mapped is usually required in order to know when overrides must be applied.

Build-Your-Own-Settings

From the above discussion it should become obvious that for any given area in the United States, the ground-water pollution potential can be estimated by choosing appropriate ranges for each DRASTIC parameter without referring to any hydrogeologic setting described in Section 6, Hydrogeologic Settings of the United States by Ground-Water Regions. In essence this is true. However, for purposes of creating a mappable unit, the settings create units which are mappable and which can be evaluated by superimposing DRASTIC. The geographic relationship also helps the user evaluate more thoroughly the characteristics of an area thereby helping create sound judgement calls and a more realistic DRASTIC Index.

How to Interpret a DRASTIC Index

The culmination of the evaluation of any hydrogeologic setting is a numerical value termed the DRASTIC Index. The higher the DRASTIC Index, the greater the ground-water pollution potential. DRASTIC is designed to yield a relative numerical value which can readily be compared to a value obtained for another setting either in the same region or in a different region. A numerical value of 160, for example, has no intrinsic meaning. That number is of value only with respect to other numbers generated by the same DRASTIC Index.

Because this document addresses a DRASTIC Index and a modified agricultural DRASTIC Index, the natural tendency is to compare the two indexes generated for one site and try to draw a conclusion. The numerical values, in and of themselves, have no intrinsic meaning so comparison between indexes should not be made; only invalid conclusions will be drawn.

References

Freeze, R. A. and J. A. Cherry, 1979. Groundwater; Prentice-Hall, 604 pp.

Heath, Ralph C., 1984. Ground-water regions of the United States; U.S. Geological Survey Water Supply Paper 2242, 78 pp.

Section 5
Impact—Risk Factors

The DRASTIC Index estimates the vulnerability of any setting to pollution on the basis of determinable geologic parameters. It does not, however, indicate a variety of other parameters that often point out the significance of the DRASTIC Index under the influence of cultural and physical modifications. For example, a site with a low DRASTIC Index, indicating moderate or low vulnerability to contamination, may be located very near to a large population center. The proximity to a population that can be exposed greatly increases the risk, or impact, of an incidence of pollution at the prospective site. Thus it can quickly be noted that not only the size of the population exposed, and the human/non-human nature of that population, but the time required for the pollutant to travel from the point of incidence to the population at risk, is a serious consideration within a given setting.

Travel time is considered only tangentially by the DRASTIC Index. It is implied by "hydraulic conductivity," but becomes interpretable, and meaningful, only when the distance to be traveled from a source of contamination to a point of concern is known, and when the gradient, or inclination of the water table is considered. Thus, the travel time of a pollutant from point of introduction until it reaches a population is not given by the DRASTIC Index, but must be evaluated separately, by persons with adequate data and expertise for each specific site.

In a similar manner, the risk to a given population is dependent on the toxicity of the pollutant being introduced. Obviously, if the pollutant being introduced is non-toxic to the population exposed, there is little or no risk to that population as a consequence of the exposure. When the pollutant is quite toxic, it is obvious that minimal exposure of the population may be very serious, even where travel time as controlled by gradient, distance, and hydraulic conductivity is great.

Essentially, the DRASTIC Index for a given setting is derived on the basis of the vulnerability of the site to an invasion of water, hence the name "hydrogeologic setting." Actually, the concern is not about the vulnerability of a setting to water, but rather with the vulnerability of that setting to contaminants. Water forms the common baseline, but the site vulnerability varies with the specific properties of the contaminant being applied. Obviously all settings cannot be mapped for all potential contaminants, so in many instances critical judgements have to be made about the risks involved. Where accidental spills are involved, these judgements must be made rapidly, conservatively, and on the basis of the best data available. Where design judgements are to be made, they should be made on the basis of adequate field and laboratory testing. It should always be kept in mind that some substances are so toxic that there are no "safe" settings available.

In addition to travel time, toxicity, and population exposed, the risk is influenced by "loading" factors. Whether the application rate is a slug application, as in an accidental spill; an intermittent application, as with herbicides, pesticides, and fertilizers; or a continuous application, such as a leaking tank or lagoon, has an obvious bearing upon the total load of material reaching an exposed population. Loading is also influenced by the concentration of the polluting substance. If the incident pollutant is highly concentrated, it is apparent that the exposed population is at much greater risk than would be the case if the pollutant were less concentrated. All of the attenuating factors, dilution, dispersion, sorption, filtration, reaction, etc. are more effective at lesser loading rates.

In order to assist in the understanding of the basic risk factors, travel time, population exposed, loading and toxicity, and how these risk factors impact the DRASTIC Index, the following acronym is suggested:

I	Inclination of the water table (gradient) Direction of slope in ft/ft (feet per foot)
M	Measured horizontal distance Distance to point of exposure in feet or miles
P	Population exposed Human or non-human
A	Application rate Slug, intermittent, or continuous
C	Concentration Concentration of pollutant, often in mg/l
T	Toxicity Degree of toxicity to the population exposed

When the DRASTIC Index of a particular setting is evaluated with regard to these parameters of impact, as a consequence of a particular pollutant, a reasonable judgement can be made with respect to the risk to the population exposed.

Section 6
Hydrogeologic Settings of the United States by Ground-Water Regions

Figure 19. Ground-water regions of the United States (After Heath, 1984).

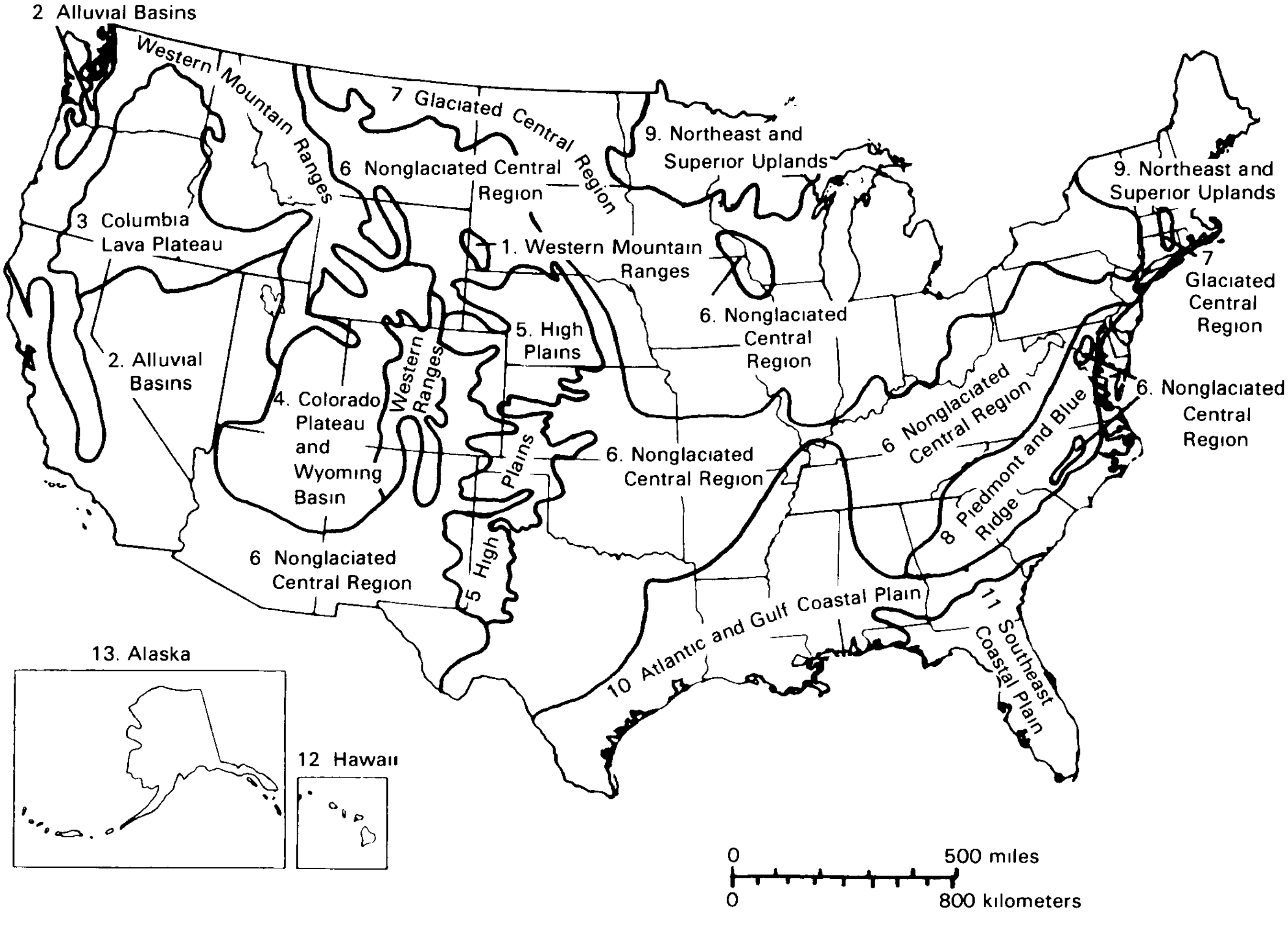


Table 18. **Hydrogeologic Settings and Associated DRASTIC Index by Region**

Number	Title	Rating
1Aa East	Mountain Slopes	65
1Ab West	Mountain Slopes	70
1Ba East	Alluvial Mountain Valleys	128
1Bb West	Alluvial Mountain Valleys	146
1Ca East	Mountain Flanks	83
1Cb West	Mountain Flanks	106
1D	Glaciated Mountain Valleys	180
1Ea East	Wide Alluvial Valleys (External Drainage)	158
1Eb West	Wide Alluvial Valleys (External Drainage)	180
1F	Coastal Beaches	196
2A	Mountain Slopes	74
2B	Alluvial Mountain Valleys	132
2C	Alluvial Fans	122
2D	Alluvial Basins (Internal Drainage)	122
2E	Playa Lakes	110
3A	Mountain Slopes	98
3B	Alluvial Mountain Valleys	168
3C	Hydraulically Connected Lava Flows	156
3D	Lava Flows Not Connected Hydraulically	105
3E	Alluvial Fans	105
4A	Resistant Ridges	88
4B	Consolidated Sedimentary Rocks	87
4C	River Alluvium	162
4D	Alluvium and Dune Sand	102
5A	Ogallala	109
5B	Alluvium	107
5C	Sand Dunes	150
5D	Playa Lakes	110
5E	Braided River Deposits	185
6A	Mountain Slopes	103
6B	Alluvial Mountain Valleys	152
6C	Mountain Flanks	105
6Da	Alternating SS, LS, SH-Thin Soil	129
6Db	Alternating SS, LS, SH-Deep Regolith	131
6E	Solution Limestone	196
6Fa	River Alluvium with Overbank	136
6Fb	River Alluvium without Overbank	187
6G	Braided River Deposits	190
6H	Triassic Basins	106
7Aa	Glacial Till Over Bedded Sedimentary Rock	93
7Ab	Glacial Till Over Outwash	127
7Ac	Glacial Till Over Solution Limestone	129
7Ad	Glacial Till Over Sandstone	99
7Ae	Glacial Till Over Shale	78
7Ba	Outwash	176
7Bb	Outwash Over Bedded Sedimentary	156
7Bc	Outwash Over Solution Limestone	186
7C	Moraine	125
7D	Buried Valley	156
7Ea	River Alluvium with Overbank Deposit	124
7Eb	River Alluvium without Overbank Deposit	191
7F	Glacial Lake Deposits	135
7G	Thin Till Over Bedded Sedimentary	111
7H	Beaches, Beach Ridges and Sand Dunes	202
8A	Mountain Slopes	75
8B	Alluvial Mountain Valleys	162
8C	Mountain Flanks	106
8D	Thick Regolith	100
8E	River Alluvium	176
8F	Mountain Crests	70
9A	Mountain Slopes	75
9B	Alluvial Mountain Valleys	180
9C	Mountain Flanks	106
9Da	Glacial Till Over Crystalline Bedrock	103
9Db	Glacial Till Over Outwash	129
9E	Outwash	190
9F	Moraine	166
9Ga	River Alluvium with Overbank	136
9Gb	River Alluvium without Overbank	191
10Aa	Confined Regional Aquifers	53
10Ab	Unconsolidated & Semi-Consolidated Shallow Surficial Aquifer	184
10Ba	River Alluvium with Overbank Deposit	132
10Bb	River Alluvium without Overbank Deposit	187
10C	Swamp	202
11A	Solution Limestone	218
11B	Coastal Deposits	191
11C	Swamp	224
11D	Beaches and Bars	190
12A	Mountain Slopes	164
12B	Alluvial Mountain Valleys	184
12C	Volcanic Uplands	165
12D	Coastal Beaches	201
13A	Alluvium	140
13B	Glacial & Glaciolacustrine Deposits of the Interior Valleys	131
13C	Coastal Lowland Deposits	140
13D	Bedrock of the Uplands and Mountains	92

Table 19. **Hydrogeologic Settings and Associated DRASTIC Index Sorted by Ratings**

Number	Title	Rating
10Aa	Confined Regional Aquifers	53
1Aa East	Mountain Slopes	65
8F	Mountain Crests	70
1Ab West	Mountain Slopes	70
2A	Mountain Slopes	74
9A	Mountain Slopes	75
8A	Mountain Slopes	75
7Ae	Glacial Till Over Shale	78
1Ca East	Mountain Flanks	83
4B	Consolidated Sedimentary Rocks	87
4A	Resistant Ridges	88
13D	Bedrock of the Uplands and Mountains	92
7Aa	Glacial Till Over Bedded Sedimentary Rock	93
3A	Mountain Slopes	98
7Ad	Glacial Till Over Sandstone	99
8D	Thick Regolith	100
4D	Alluvium and Dune Sand	102
9Da	Glacial Till Over Crystalline Bedrock	103
6A	Mountain Slopes	103
3D	Lava Flows Not Connected Hydraulically	105
3E	Alluvial Fans	105
6C	Mountain Flanks	105
1Cb West	Mountain Flanks	106
6H	Triassic Basins	106
8C	Mountain Flanks	106
9C	Mountain Flanks	106
5B	Alluvium	107
5A	Ogallala	109
2E	Playa Lakes	110
5D	Playa Lakes	110
7G	Thin Till Over Bedded Sedimentary	111
2D	Alluvial Basins (Internal Drainage)	122
2C	Alluvial Fans	122
7Ea	River Alluvium with Overbank Deposit	124
7C	Moraine	125
7Ab	Glacial Till Over Outwash	127
1Ba East	Alluvial Mountain Valleys	128
7Ac	Glacial Till Over Solution Limestone	129
9Db	Glacial Till Over Outwash	129

Table 19. (Continued)

Number	Title	Rating
6Da	Alternating SS, LS, SH-Thin Soil	129
13B	Glacial & Glaciolacustrine Deposits of the Interior Valleys	131
6Db	Alternating SS, LS, SH-Deep Regolith	131
10Ba	River Alluvium with Overbank Deposit	132
2B	Alluvial Mountain Valleys	132
7F	Glacial Lake Deposits	135
9Ga	River Alluvium with Overbank	136
6Fa	River Alluvium with Overbank	136
13A	Alluvium	140
13C	Coastal Lowland Deposits	140
1Bb West	Alluvial Mountain Valleys	146
5C	Sand Dunes	150
6B	Alluvial Mountain Valleys	152
3C	Hydraulically Connected Lava Flows	156
7Bb	Outwash Over Bedded Sedimentary	156
7D	Buried Valley	156
1Ea East	Wide Alluvial Valleys (External Drainage)	158
4C	River Alluvium	162
8B	Alluvial Mountain Valleys	162
12A	Mountain Slopes	164
12C	Volcanic Uplands	165
9F	Moraine	166
3B	Alluvial Mountain Valleys	168
7Ba	Outwash	176
8E	River Alluvium	176
1Eb West	Wide Alluvial Valleys (External Drainage)	180
1D	Glaciated Mountain Valleys	180
9B	Alluvial Mountain Valleys	180
10Ab	Unconsolidated & Semi-Consolidated Shallow Surficial Aquifer	184
12B	Alluvial Mountain Valleys	184
5E	Braided River Deposits	185
7Bc	Outwash Over Solution Limestone	186
6Fb	River Alluvium without Overbank	187
10Bb	River Alluvium without Overbank Deposit	187
6G	Braided River Deposits	190
11D	Beaches and Bars	190
9E	Outwash	190
11B	Coastal Deposits	191
9Gb	River Alluvium without Overbank	191
7Eb	River Alluvium without Overbank Deposit	191
6E	Solution Limestone	196
1F	Coastal Beaches	196
12D	Coastal Beaches	201
7H	Beaches, Beach Ridges and Sand Dunes	202
10C	Swamp	202
11A	Solution Limestone	218
11C	Swamp	224

Table 20. Hydrogeologic Settings and Associated DRASTIC Index Sorted by Setting Title

Number	Title	Rating
2D	Alluvial Basins (Internal Drainage)	122
2C	Alluvial Fans	122
3E	Alluvial Fans	105
12B	Alluvial Mountain Valleys	184
1Ba East	Alluvial Mountain Valleys	128
1Bb West	Alluvial Mountain Valleys	146
2B	Alluvial Mountain Valleys	132
3B	Alluvial Mountain Valleys	168
6B	Alluvial Mountain Valleys	152
8B	Alluvial Mountain Valleys	162
9B	Alluvial Mountain Valleys	180
13A	Alluvium	140
5B	Alluvium	107
4D	Alluvium and Dune Sand	102
6Db	Alternating SS,LS,SH-Deep Regolith	131
6Da	Alternating SS,LS,SH-Thin Soil	129
11D	Beaches and Bars	190
7H	Beaches, Beach Ridges and Sand Dunes	202
13D	Bedrock of the Uplands and Mountains	92
5E	Braided River Deposits	185
6G	Braided River Deposits	190
7D	Buried Valley	156
1F	Coastal Beaches	196
12D	Coastal Beaches	201
11B	Coastal Deposits	191
13C	Coastal Lowland Deposits	140
10Aa	Confined Regional Aquifers	53
4B	Consolidated Sedimentary Rocks	87
13B	Glacial & Glaciolacustrine Deposits of the Interior Valleys	131
7F	Glacial Lake Deposits	135
7Aa	Glacial Till Over Bedded Sedimentary Rock	93
9Da	Glacial Till Over Crystalline Bedrock	103
7Ab	Glacial Till Over Outwash	127
9Db	Glacial Till Over Outwash	129
7Ad	Glacial Till Over Sandstone	99
7Ae	Glacial Till Over Shale	78
7Ac	Glacial Till Over Solution Limestone	129
1D	Glaciated Mountain Valleys	180
3C	Hydraulically Connected Lava Flows	156
3D	Lava Flows Not Connected Hydraulically	105
7C	Moraine	125
9F	Moraine	166
8F	Mountain Crests	70
1Ca East	Mountain Flanks	83
6C	Mountain Flanks	105
1Cb West	Mountain Flanks	106
8C	Mountain Flanks	106
9C	Mountain Flanks	106
12A	Mountain Slopes	164
1Aa East	Mountain Slopes	65
1Ab West	Mountain Slopes	70
2A	Mountain Slopes	74
3A	Mountain Slopes	98
6A	Mountain Slopes	103
8A	Mountain Slopes	75
9A	Mountain Slopes	75
5A	Ogallala	109
7Ba	Outwash	176
9E	Outwash	190
7Bb	Outwash Over Bedded Sedimentary	156
7Bc	Outwash Over Solution Limestone	186
2E	Playa Lakes	110
5D	Playa Lakes	110
4A	Resistant Ridges	88
4C	River Alluvium	162
8E	River Alluvium	176
6Fa	River Alluvium with Overbank	136
9Ga	River Alluvium with Overbank	136
10Bb	River Alluvium with Overbank Deposit	132
7Ea	River Alluvium with Overbank Deposit	124
6Fb	River Alluvium without Overbank	187
9Gb	River Alluvium without Overbank	191
10Bb	River Alluvium without Overbank Deposit	187
7Eb	River Alluvium without Overbank Deposit	191
5C	Sand Dunes	150
11A	Solution Limestone	218
6E	Solution Limestone	196

Table 20. (Continued)

Number	Title	Rating
10C	Swamp	202
11C	Swamp	224
8D	Thick Regolith	100
7G	Thin Till Over Bedded Sedimentary	111
6H	Triassic Basins	106
10Ab	Unconsolidated & Semi-Consolidated Shallow Surficial Aquifer	184
12C	Volcanic Uplands	165
1Ea East	Wide Alluvial Valleys (External Drainage)	158
1Eb West	Wide Alluvial Valleys (External Drainage)	180

Table 21. Hydrogeologic Settings and Associated Agricultural DRASTIC Index by Region

Number	Title	Rating
1Aa East	Mountain Slopes	91
1Ab West	Mountain Slopes	97
1Ba East	Alluvial Mountain Valleys	166
1Bb West	Alluvial Mountain Valleys	184
1Ca East	Mountain Flanks	99
1Cb West	Mountain Flanks	122
1D	Glaciated Mountain Valleys	214
1Ea East	Wide Alluvial Valleys (External Drainage)	192
1Eb West	Wide Alluvial Valleys (External Drainage)	214
1F	Coastal Beaches	221
2A	Mountain Slopes	105
2B	Alluvial Mountain Valleys	165
2C	Alluvial Fans	155
2D	Alluvial Basins (Internal Drainage)	157
2E	Playa Lakes	139
3A	Mountain Slopes	122
3B	Alluvial Mountain Valleys	202
3C	Hydraulically Connected Lava Flows	182
3D	Lava Flows Not Connected Hydraulically	143
3E	Alluvial Fans	123
4A	Resistant Ridges	117
4B	Consolidated Sedimentary Rocks	108
4C	River Alluvium	186
4D	Alluvium and Dune Sand	131
5A	Ogallala	136
5B	Alluvium	135
5C	Sand Dunes	177
5D	Playa Lakes	139
5E	Braided River Deposits	216
6A	Mountain Slopes	132
6B	Alluvial Mountain Valleys	176
6C	Mountain Flanks	126
6Da	Alternating SS, LS, SH-Thin Soil	155
6Db	Alternating SS, LS, SH-Deep Regolith	160
6E	Solution Limestone	216
6Fa	River Alluvium with Overbank	156
6Fb	River Alluvium without Overbank	209
6G	Braided River Deposits	221
6H	Triassic Basins	135
7Aa	Glacial Till Over Bedded Sedimentary Rock	117
7Ab	Glacial Till Over Outwash	145
7Ac	Glacial Till Over Solution Limestone	145
7Ad	Glacial Till Over Sandstone	121
7Ae	Glacial Till Over Shale	103
7Ba	Outwash	196
7Bb	Outwash Over Bedded Sedimentary	182
7Bc	Outwash Over Solution Limestone	206
7C	Moraine	148
7D	Buried Valley	178
7Ea	River Alluvium with Overbank Deposit	149
7Eb	River Alluvium without Overbank Deposit	224
7F	Glacial Lake Deposits	165
7G	Thin Till Over Bedded Sedimentary	135
7H	Beaches, Beach Ridges and Sand Dunes	225
8A	Mountain Slopes	102
8B	Alluvial Mountain Valleys	185
8C	Mountain Flanks	123
8D	Thick Regolith	117
8E	River Alluvium	198
8F	Mountain Crests	113
9A	Mountain Slopes	102
9B	Alluvial Mountain Valleys	202
9C	Mountain Flanks	122
9Da	Glacial Till Over Crystalline Bedrock	134
9Db	Glacial Till Over Outwash	153
9E	Outwash	210
9F	Moraine	180
9Ga	River Alluvium with Overbank	156
9Gb	River Alluvium without Overbank	213
10Aa	Confined Regional Aquifers	53
10Ab	Unconsolidated & Semi-Consolidated Shallow Surficial Aquifer	206
10Ba	River Alluvium with Overbank Deposit	157
10Bb	River Alluvium without Overbank Deposit	220
10C	Swamp	233
11A	Solution Limestone	243
11B	Coastal Deposits	224
11C	Swamp	251
11D	Beaches and Bars	225
12A	Mountain Slopes	177
12B	Alluvial Mountain Valleys	192
12C	Volcanic Uplands	174
12D	Coastal Beaches	230
13A	Alluvium	164
13B	Glacial & Glaciolacustrine Deposits of the Interior Valleys	158
13C	Coastal Lowland Deposits	164
13D	Bedrock of the Uplands and Mountains	118

Table 22. Hydrogeologic Settings and Associated Agricultural DRASTIC Index Sorted by Ratings

Number	Title	Rating
10Aa	Confined Regional Aquifers	53
1Aa East	Mountain Slopes	91
1Ab West	Mountain Slopes	97
1Ca East	Mountain Flanks	99
8A	Mountain Slopes	102
9A	Mountain Slopes	102
7Ae	Glacial Till Over Shale	103
2A	Mountain Slopes	105
4B	Consolidated Sedimentary Rocks	108
8F	Mountain Crests	113
7Aa	Glacial Till Over Bedded Sedimentary Rock	117
4A	Resistant Ridges	117
8D	Thick Regolith	117
13D	Bedrock of the Uplands and Mountains	118
7Ad	Glacial Till Over Sandstone	121
1Cb West	Mountain Flanks	122
9C	Mountain Flanks	122
3A	Mountain Slopes	122
3E	Alluvial Fans	123
8C	Mountain Flanks	123
6C	Mountain Flanks	126

Table 22. (Continued)

Number	Title	Rating
4D	Alluvium and Dune Sand	131
6A	Mountain Slopes	132
9Da	Glacial Till Over Crystalline Bedrock	134
5B	Alluvium	135
6H	Triassic Basins	135
7G	Thin Till Over Bedded Sedimentary	135
5A	Ogallala	136
5D	Playa Lakes	139
2E	Playa Lakes	139
3D	Lava Flows Not Connected Hydraulically	143
7Ab	Glacial Till Over Outwash	145
7Ac	Glacial Till Over Solution Limestone	145
7C	Moraine	148
7Ea	River Alluvium with Overbank Deposit	149
9Db	Glacial Till Over Outwash	153
2C	Alluvial Fans	155
6Da	Alternating SS,LS,SH-Thin Soil	155
6Fa	River Alluvium with Overbank	156
9Ga	River Alluvium with Overbank	156
2D	Alluvial Basins (Internal Drainage)	157
10Ba	River Alluvium with Overbank Deposit	157
13B	Glacial & Glaciolacustrine Deposits of the Interior Valleys	158
6Db	Alternating SS,LS,SH-Deep Regolith	160
13A	Alluvium	164
13C	Coastal Lowland Deposits	164
2B	Alluvial Mountain Valleys	165
7F	Glacial Lake Deposits	165
1Ba East	Alluvial Mountain Valleys	166
12C	Volcanic Uplands	174
6B	Alluvial Mountain Valleys	176
5C	Sand Dunes	177
12A	Mountain Slopes	177
7D	Buried Valley	178
9F	Moraine	180
3C	Hydraulically Connected Lava Flows	182
7Bb	Outwash Over Bedded Sedimentary	182
1Bb West	Alluvial Mountain Valleys	184
8B	Alluvial Mountain Valleys	185
4C	River Alluvium	186
12B	Alluvial Mountain Valleys	192
1Ea East	Wide Alluvial Valleys (External Drainage)	192
7Ba	Outwash	196
8E	River Alluvium	198
3B	Alluvial Mountain Valleys	202
9B	Alluvial Mountain Valleys	202
10Ab	Unconsolidated & Semi-Consolidated Shallow Surficial Aquifer	206
7Bc	Outwash Over Solution Limestone	206
6Fb	River Alluvium without Overbank	209
9E	Outwash	210
9Gb	River Alluvium without Overbank	213
1Eb West	Wide Alluvial Valleys (External Drainage)	214
1D	Glaciated Mountain Valleys	214
6E	Solution Limestone	216
5E	Braided River Deposits	216
10Bb	River Alluvium without Overbank Deposit	220
1F	Coastal Beaches	221
6G	Braided River Deposits	221
11B	Coastal Deposits	224
7Eb	River Alluvium without Overbank Deposit	224
7H	Beaches, Beach Ridges and Sand Dunes	225
11D	Beaches and Bars	225
12D	Coastal Beaches	230
10C	Swamp	233
11A	Solution Limestone	243
11C	Swamp	251

Table 23. Hydrogeologic Settings and Associated Agricultural DRASTIC Index Sorted by Setting Title

Number	Title	Rating
2D	Alluvial Basins (Internal Drainage)	157
2C	Alluvial Fans	155
3E	Alluvial Fans	123
8B	Alluvial Mountain Valleys	185
2B	Alluvial Mountain Valleys	165
6B	Alluvial Mountain Valleys	176
3B	Alluvial Mountain Valleys	202
1Bb West	Alluvial Mountain Valleys	184
1Ba East	Alluvial Mountain Valleys	166
9B	Alluvial Mountain Valleys	202
12B	Alluvial Mountain Valleys	192
5B	Alluvium	135
13A	Alluvium	164
4D	Alluvium and Dune Sand	131
6Db	Alternating SS,LS,SH-Deep Regolith	160
6Da	Alternating SS,LS,SH-Thin Soil	155
11D	Beaches and Bars	225
7H	Beaches, Beach Ridges and Sand Dunes	225
13D	Bedrock of the Uplands and Mountains	118
5E	Braided River Deposits	216
6G	Braided River Deposits	221
7D	Buried Valley	178
1F	Coastal Beaches	221
12D	Coastal Beaches	230
11B	Coastal Deposits	224
13C	Coastal Lowland Deposits	164
10Aa	Confined Regional Aquifers	53
4B	Consolidated Sedimentary Rocks	108
13B	Glacial & Glaciolacustrine Deposits of the Interior Valleys	158
7F	Glacial Lake Deposits	165
7Aa	Glacial Till Over Bedded Sedimentary Rock	117
9Da	Glacial Till Over Crystalline Bedrock	134
7Ab	Glacial Till Over Outwash	145
9Db	Glacial Till Over Outwash	153
7Ad	Glacial Till Over Sandstone	121
7Ae	Glacial Till Over Shale	103
7Ac	Glacial Till Over Solution Limestone	145
1D	Glaciated Mountain Valleys	214
3C	Hydraulically Connected Lava Flows	182
3D	Lava Flows Not Connected Hydraulically	143
7C	Moraine	148
9F	Moraine	180
8F	Mountain Crests	113
1Cb West	Mountain Flanks	122
6C	Mountain Flanks	126
8C	Mountain Flanks	123
9C	Mountain Flanks	122
1Ca East	Mountain Flanks	99
12A	Mountain Slopes	177
9A	Mountain Slopes	102
2A	Mountain Slopes	105
6A	Mountain Slopes	132
1Ab West	Mountain Slopes	97
1Aa East	Mountain Slopes	91
3A	Mountain Slopes	122
8A	Mountain Slopes	102
5A	Ogallala	136
7Ba	Outwash	196
9E	Outwash	210
7Bb	Outwash Over Bedded Sedimentary	182
7Bc	Outwash Over Solution Limestone	206
5D	Playa Lakes	139
2E	Playa Lakes	139
4A	Resistant Ridges	117
8E	River Alluvium	198

Table 23. (Continued)

Number	Title	Rating
4C	River Alluvium	186
6Fa	River Alluvium with Overbank	156
9Ga	River Alluvium with Overbank	156
10Ba	River Alluvium with Overbank Deposit	157
7Ea	River Alluvium with Overbank Deposit	149
6Fb	River Alluvium without Overbank	209
9Gb	River Alluvium without Overbank	213
10Bb	River Alluvium without Overbank Deposit	220
7Eb	River Alluvium without Overbank Deposit	224
5C	Sand Dunes	177
6E	Solution Limestone	216
11A	Solution Limestone	243
11C	Swamp	251
10C	Swamp	233
8D	Thick Regolith	117
7G	Thin Till Over Bedded Sedimentary	135
6H	Triassic Basins	135
10Ab	Unconsolidated & Semi-Consolidated Shallow Surficial Aquifer	206
12C	Volcanic Uplands	174
1Eb West	Wide Alluvial Valleys (External Drainage)	214
1Ea East	Wide Alluvial Valleys (External Drainage)	192

Table 24. **Summary of the Principal Physical and Hydrologic Characteristics of the Ground-Water Regions of the United States (after Heath, 1984)**

Region No.	Name	Components of the system														Characteristics of dominant aquifers																				
																Water-bearing openings					Composition			Storage and transmission properties							Recharge and discharge conditions					
		Unconfined aquifer			Confining beds			Confined aquifers				Presence and arrangement				Primary		Secondary			Degree of *solubility*			Porosity			Transmissivity				Recharge			Discharge		
		Hydrologically insignificant	Minor aquifer or not very productive	Dominant aquifer	Hydrologically insignificant	Thin, discontinuous, or v leaky	Interlayered with aquifers	Hydrologically insignificant	Not highly productive	Multiple productive aquifers	The dominant productive aquifer	Single unconfined aquifer	Two interconnected aquifers	Unconfined aquifer, confining bed, confined aquifer	*complex interbedded sequence*	Pores in unconsolidated dep	Pores in semiconsolidated rocks	Tubes and cooling cracks in lava	Fractures and faults	Solution-enlarged openings	Insoluble	Mixed soluble and insoluble	Soluble	Large (>0.2)	Moderate (0.01-0.2)	Small (<0.01)	Large (>2,500 m^2day^{-1})	Moderate (250-2,500 m^2day^{-1})	Small (25-250 m^2day^{-1})	Very small (<25 m^2day^{-1})	*Uplands between streams*	Losing streams	Leakage through confining beds	Springs and surface seepage	Evaporation and basin sinks	Into other aquifers
1	Western Mountain Ranges		X		X				X				X			X			X		X				X				X		X	X		X		
2	Alluvial Basins			X			X			X					X	X					X			X			X					X			X	X
3	Columbia Lava Plateau		X				X			X					X	X		X	X		X					X	X					X		X		
4	Colorado Plateau and Wyoming Basin	X					X			X					X		X		X		X					X			X		X		X	X		
5	High Plains			X	X			X				X				X					X			X			X					X		X		
6	Nonglaciated Central Region		X				X			X					X		X		X	X		X				X		X			X		X	X		X
7	Glaciated Central Region		X				X			X					X	X	X		X	X		X			X			X					X			X
8	Piedmont and Blue Ridge		X		X				X				X			X			X		X					X				X	X			X		
9	Northeast and Superior Uplands		X			X			X				X			X			X		X					X			X		X			X		
10	Atlantic and Gulf Coastal Plain		X				X			X					X	X				X		X			X			X			X		X	X		X
11	Southeast Coastal Plain		X				X				X			X		X				X			X	X			X				X		X	X		
12	Hawaii			X		X		X				X						X			X			X			X				X	X		X		
13	Alaska			X		X			X						X	X			X			X			X			X				X		X		

Table 25. **Common Ranges for the Hydraulic Characteristics of Ground-Water Regions of The United States (after Heath, 1984)**

Region No	Region	Geologic situation	Common ranges in hydraulic characteristics of the dominant aquifers															
			Transmissivity				Hydraulic conductivity				Recharge rate				Well yield			
			m^2day^{-1}		ft^2day^{-1}		$m\ day^{-1}$		$ft\ day^{-1}$		$mm\ yr^{-1}$		$in\ yr^{-1}$		m^3min^{-1}		$gal\ min^{-1}$	
1	Western Mountain Ranges	Mountains with thin soils over fractured rocks, alternating with narrow alluvial and, in part, glaciated valleys		100	5	5,000,000	0.0003	15	0.001	50	3	50	0.1	2	0.04	0.4	10	100
2	Alluvial Basins	Thick[1] alluvial (locally glacial) deposits in basins and valleys bordered by mountains	20	20,000	2,000	200,000	30	600	100	2,000	0.03	30	0.001	1	0.04	20	100	5,000
3	Columbia Lava Plateau	Thick sequence of lava flows interbedded with unconsolidated deposits and overlain by thin soils	2,000	500,000	20,000	5,000,000	200	3,000	500	10,000	5	300	0.2	10	0.4	80	100	20,000
4	Colorado Plateau and Wyoming Basin	Thin[1] soils over fractured sedimentary rocks	0.5	100	5	1,000	0.003	2	0.01	5	0.3	50	0.01	2	0.04	2	10	1,000
5	High Plains	Thick alluvial deposits over fractured sedimentary rocks	1,000	10,000	10,000	100,000	30	300	100	1,000	5	80	0.2	3	0.4	10	100	3,000
6	Nonglaciated Central region	Thin regolith over fractured sedimentary rocks	300	10,000	3,000	100,000	3	300	10	1,000	5	500	0.2	20	0.4	20	100	5,000
7.	Glaciated Central region	Thick glacial deposits over fractured sedimentary rocks	100	2,000	1,000	20,000	2	300	5	1,000	5	300	0.2	10	0.2	2	50	500
8	Piedmont and Blue Ridge	Thick regolith over fractured crystalline and metamorphosed sedimentary rocks	9	200	100	2,000	0.001	1	0.003	3	30	300	1	10	0.2	2	50	500
9	Northeast and Superior Uplands	Thick glacial deposits over fractured crystalline rocks	50	500	500	5,000	2	30	5	100	30	300	1	10	0.1	1	20	200
10	Atlantic and Gulf Coastal Plain	Complexly interbedded sands, silts, and clays	500	10,000	5,000	100,000	3	100	10	400	50	500	2	20	0.4	20	100	5,000
11	Southeast Coastal Plain	Thick layers of sand and clay over semiconsolidated carbonate rocks	1,000	100,000	10,000	1,000,000	30	3,000	100	10,000	30	500	1	20	4	80	1,000	20,000
12	Hawaiian Islands	Lava flows segmented by dikes, interbedded with ash deposits, and partly overlain by alluvium	10,000	100,000	100,000	1,000,000	200	3,000	500	10,000	30	1,000	1	40	0.4	20	100	5,000
13	Alaska	Glacial and alluvial deposits in part perennially frozen and overlying crystalline, metamorphic, and sedimentary rocks	100	10,000	1,000	100,000	30	600	100	2,000	3	300	0.1	10	0.04	4	10	1,000

Table 26. **Ranges and Ratings for Depth to Water**

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

Table 27. **Ranges and Ratings for Net Recharge**

Net Recharge (inches)	
Range	Rating
0-2	1
2-4	3
4-7	6
7-10	8
10+	9
Weight: 4	Agricultural Weight: 4

Table 28. **Ranges and Ratings for Aquifer Media**

Aquifer Media		
Range	Rating	Typical Rating
Massive Shale	1-3	2
Metamorphic/Igneous	2-5	3
Weathered Metamorphic/Igneous	3-5	4
Thin Bedded Sandstone, Limestone, Shale Sequences	5-9	6
Massive Sandstone	4-9	6
Massive Limestone	4-9	6
Sand and Gravel	6-9	8
Basalt	2-10	9
Karst Limestone	9-10	10
Weight: 3	Agricultural Weight: 3	

Table 29. **Ranges and Ratings for Soil Media**

Soil Media	
Range	*Rating*
Thin or Absent	10
Gravel	10
Sand	9
Shrinking and/or Aggregated Clay	7
Sandy Loam	6
Loam	5
Silty Loam	4
Clay Loam	3
Nonshrinking and Nonaggregated Clay	1
Weight: 2	Agricultural Weight: 5

Table 30. **Ranges and Ratings for Topography**

Topography (percent slope)	
Range	Rating
0-2	10
2-6	9
6-12	5
12-18	3
18+	1
Weight: 1	Agricultural Weight: 3

Table 31. **Ranges and Ratings for Impact of Vadose Zone Media**

Impact of Vadose Zone Media		
Range	Rating	Typical Rating
Silt/Clay	1-2	1
Shale	2-5	3
Limestone	2-7	6
Sandstone	4-8	6
Bedded Limestone, Sandstone, Shale	4-8	6
Sand and Gravel with significant Silt and Clay	4-8	6
Metamorphic/Igneous	2-8	4
Sand and Gravel	6-9	8
Basalt	2-10	9
Karst Limestone	8-10	10
Weight: 5	Agricultural Weight: 4	

Table 32. **Ranges and Ratings for Hydraulic Conductivity**

Hydraulic Conductivity (GPD/FT^2)	
Range	Rating
1-100	1
100-300	2
300-700	4
700-1000	6
1000-2000	8
2000+	10
Weight: 3	Agricultural Weight: 2

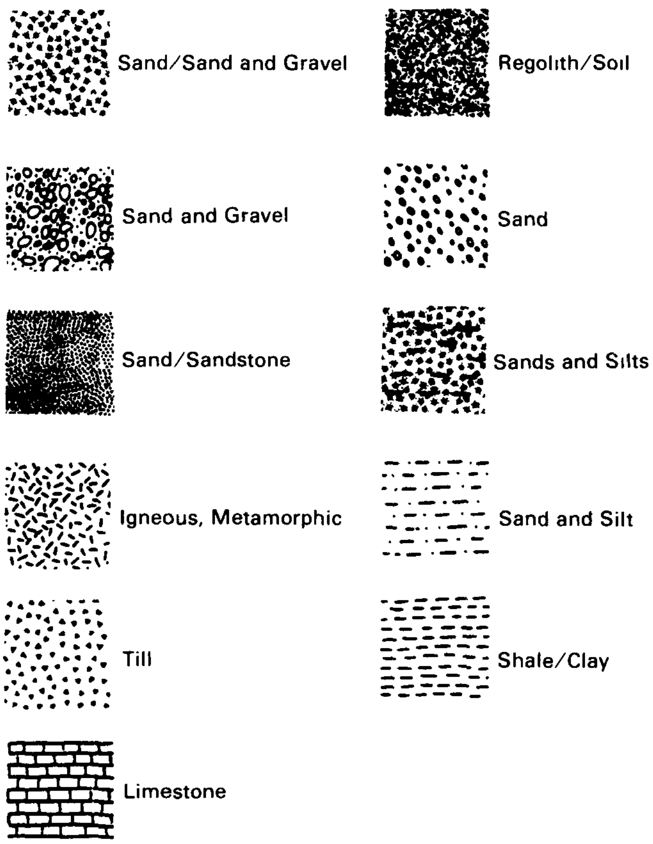
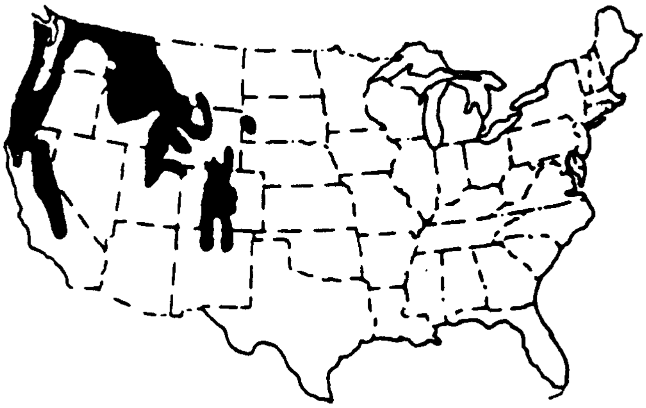
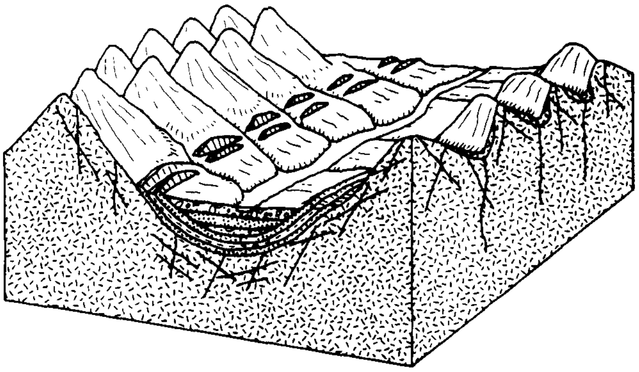


Figure 20. **Map legend.**

1. *Western Mountain Ranges*

(Mountains with thin soils over fractured rocks, alternating with narrow alluvial and, in part, glaciated valleys)





The Western Mountain Ranges encompass three areas totaling 708,000 km². The largest area extends in an arc from the Sierra Nevada in California, north through the Coast Ranges and Cascade Mountains in Oregon and Washington, and east and south through the Rocky Mountains in Idaho and Montana into the Bighorn Mountains in Wyoming and the Wasatch and Uinta Mountains in Utah. The second area includes the southern Rocky Mountains, which extend from the Laramie Range in southeastern Wyoming through Central Colorado into the Sangre de Cristo Range in northern New Mexico. The smallest area includes the part of the Black Hills in South Dakota in which Precambrian rocks are exposed. Summits in the Rocky Mountains and Sierra Nevada exceed 3,500 m. The general appearance of the Western Mountain Ranges, with the exception of the Black Hills, is tall, massive mountains alternating with relatively narrow, steep-sided valleys. The summits and sides of the mountains in much of the region have been carved into distinctive shapes by mountain glaciers. The ranges that comprise the southern Rocky Mountains are separated by major lowlands that include North Park, Middle Park, South Park, and the Wet Mountain Valley. These lowlands occupy downfolded or down-faulted structural troughs as much as 70 km wide and 160 km long. The mountains in the Black Hills are lower in altitude than most of the mountains in other parts of the region.

As would be expected in such a large region, both the origin of the mountains and the rocks that form them are complex. Most of the mountain ranges are underlain by granitic and metamorphic rocks flanked by consolidated sedimentary rocks of Paleozoic to Cenozoic age. The other ranges, including the San Juan Mountains in southwestern Colorado and the Cascade Mountains in Washington and Oregon, are underlain by lavas and other igneous rocks.

The summits and slopes of most of the mountains consist of bedrock exposures or of bedrock covered by a layer of boulders and other rock fragments produced by frost action and other weathering processes acting on the bedrock. This layer is generally only a few meters thick on the upper slopes but forms a relatively thick apron along the base of the mountains. The narrow valleys are underlain by relatively thin, coarse, bouldery alluvium washed from the higher slopes. The large synclinal valleys and those that occupy down-faulted structural troughs are underlain by moderately thick deposits of coarse-grained alluvium transported by streams from the adjacent mountains.

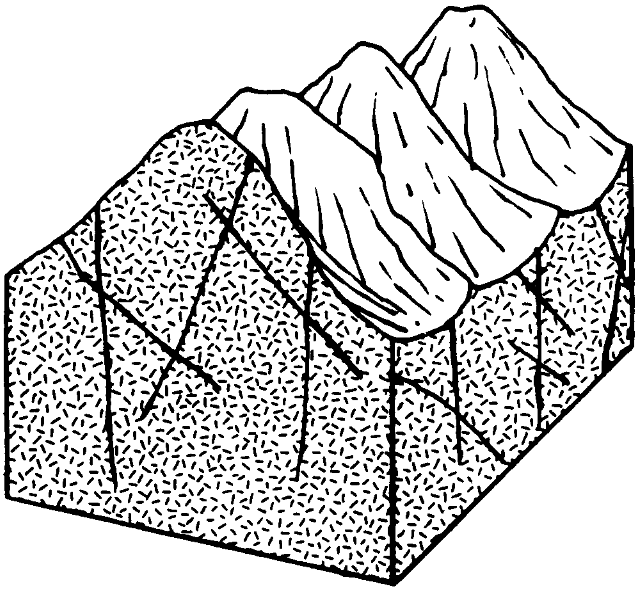
The Western Mountain Ranges and the mountain ranges in adjacent regions are the principal sources of water supplies developed at lower altitudes in the western half of the conterminous United States. As McGuinness (1963) noted, the mountains of the west are moist "islands" in a sea of desert or semidesert that covers the western half of the Nation. The mountains force moisture-laden air masses moving eastward from the Pacific to rise to higher and cooler altitudes. As the air cools, moisture condenses into clouds and precipitates. The heaviest precipitation falls on the western slopes; thus, these slopes are the major source of runoff and are also the most densely vegetated. Much of the precipitation falls as snow during the winter, and its slow melting, starting at the lower altitudes in early spring, maintains streamflow at large rates until late June or early July. Small glaciers occur in the higher mountain ranges, especially in the northern Rocky Mountains, the Cascades, and the Sierra Nevada; locally, as in northern Washington they also provide significant sources of summer runoff.

Melting snow and rainfall at the higher altitudes in the region provide abundant water for ground-water recharge. However, the thin soils and bedrock fractures in areas underlain by crystalline rocks fill quickly, and the remaining water runs off overland to streams. Because of their small storage capacity, the underground openings provide limited base runoff to the streams, which at the higher altitudes flow only during rains or snowmelt periods. Thus, at the higher altitudes in this region underlain by crystalline rocks, relatively little opportunity exists for development of ground-water supplies. The best opportunities exist in valleys that contain at least moderate thicknesses of saturated alluvium or in areas underlain by permeable sedimentary or volcanic rocks. Ground-water supplies in the valleys are obtained both from wells drawing from the alluvium and from wells drawing from the underlying rocks. The yields of wells in crystalline bedrock and wells drawing water from small, thin deposits of alluvium are generally adequate only for domestic and stock needs. Large yields can be obtained from the alluvial deposits that overlie the major lowlands and from wells completed in permeable sedimentary or volcanic rocks.

Western Mountain Ranges

(1Aa) Mountain Slopes—East

This hydrogeologic setting is characterized by steep slopes on the sides of mountains, a thin soil cover and highly fractured bedrock. Ground water is obtained primarily from the fractures in the bedrock which may be of sedimentary, metamorphic or igneous origin. The fractures provide localized sources of ground water and well yields are typically limited even though the hydraulic conductivity is often high because of the fractures. Due to the steep slopes, thin soil and small storage capacity of the fractures, runoff is significant. Thicker weathered zones (soils) may develop locally particularly on talus slopes with local perched zones common. These eastern facing slopes are located in the rain shadow of the mountains and only limited rainfall is derived from the moisture laden prevailing westerly winds, thus ground-water recharge rarely exceeds 1 inch/year. Ground-water levels are extremely variable but are typically deep. Most of these areas are water deficient on an annual basis. The migration of pollutants introduced at the surface will be dependent on the current climatic conditions; pollutants will tend to infiltrate easier and further during wet periods as opposed to dry periods.



Setting 1 Aa East Mountain Slopes

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	100+	5	1	5
Net Recharge	0-2	4	1	4
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	2	10	20
Topography	18+%	1	1	1
Impact Vadose Zone	Metamorphic/ Igneous	5	4	20
Hydraulic Conductivity	100-300	3	2	6

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Setting 1 Aa East Mountain Slopes

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	100+	5	1	5
Net Recharge	0-2	4	1	4
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	5	10	50
Topography	18+%	3	1	3
Impact Vadose Zone	Metamorphic/ Igneous	4	4	16
Hydraulic Conductivity	100-300	2	2	4

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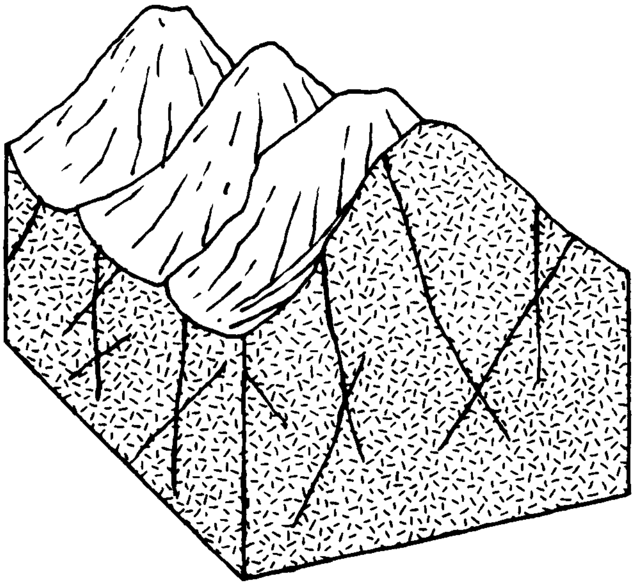
Western Mountain Ranges

(1Ab) Mountain Slopes—West

This setting is similar to (1Aa) Mountain Slopes—East except that ground-water levels are typically more shallow and precipitation greatly exceeds the amount which falls on the eastern slopes. Even though rainfall is more abundant, recharge is still low due to the steepness of the slopes and density of the underlying bedrock and may only exceed 2 inches/year in places where precipitation is very high and soil cover is unusually favorable. Due to increased precipitation, pollutants may tend to migrate to the water table more rapidly, but be more diluted, than on the comparable eastern slopes.



Setting 1 Ab West Mountain Slopes

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	0-2	4	1	4
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	2	10	20
Topography	18+%	1	1	1
Impact Vadose Zone	Metamorphic/ Igneous	5	4	20
Hydraulic Conductivity	100-300	3	2	6
		DRASTIC Index		70

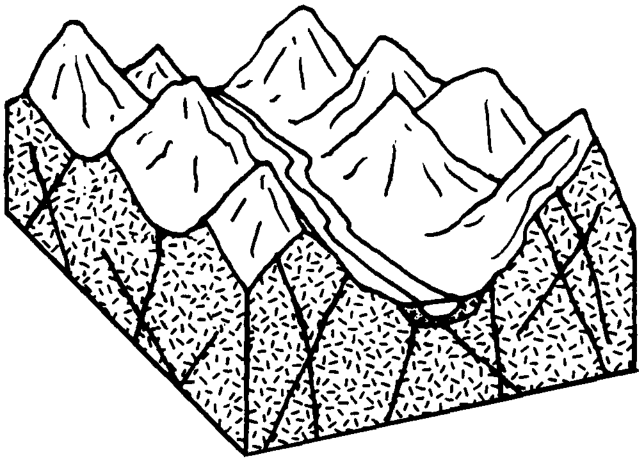
Setting 1 Ab West Mountain Slopes

Feature	Range	Agricultural		
		Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	0-2	4	1	4
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	5	10	50
Topography	18+%	3	1	3
Impact Vadose Zone	Metamorphic/ Igneous	4	4	16
Hydraulic Conductivity	100-300	2	2	4
		Agricultural DRASTIC Index		97

Western Mountain Ranges

(1Ba) Alluvial Mountain Valleys—East

This hydrogeologic setting of eastward facing interior valleys is characterized by thin bouldery alluvium which overlies fractured bedrock of sedimentary, metamorphic or igneous origin. The alluvium, which is derived from the surrounding steep slopes serves as a localized source of water. Where soil cover exists, it typically is gravel sized and offers little protection from pollution. Water levels are typically moderately deep because of the lack of precipitation on the eastern slopes and the low net recharge. Ground water is obtained from the coarser grained deposits within the valley, but these deposits also have a fraction of finer grained deposits which can influence water movement. Ground water may also be obtained from the fractures in the underlying bedrock which are typically in direct hydraulic connection with the overlying alluvium. Since these valleys are usually structurally controlled, there is the possibility that any pollutants introduced at the surface may migrate into the fractures beneath the alluvium and disperse rapidly from the site of incidence.



Setting 1 Ba East Alluvial Mtn. Valleys

Feature	Range	General Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Gravel	2	10	20
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	100-300	3	2	6

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Setting 1 Ba East Alluvial Mtn. Valleys

Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Gravel	5	10	50
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	100-300	2	2	4

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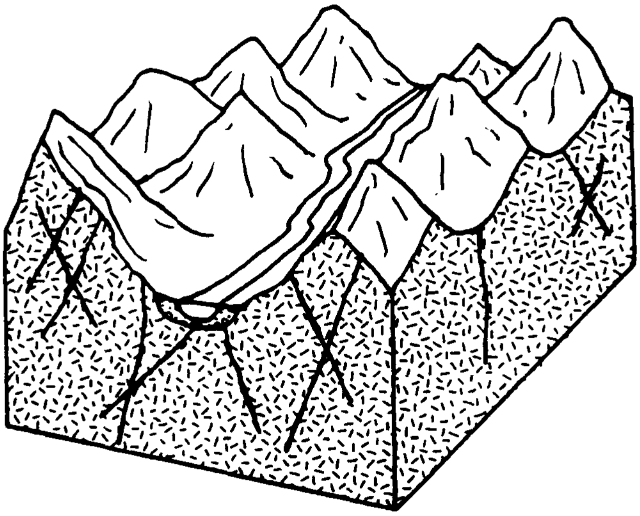
Western Mountain Ranges

(1Bb) Alluvial Mountain Valleys—West

This setting, which includes coastal valleys and westward-sloping interior valleys, is similar to (1Ba) Narrow Alluvial Valleys—East. Water Levels are typically shallower due to higher amounts of precipitation and subsequently greater ground-water recharge. Soils tend to be deeper with better developed soil profiles. Bedrock weathering is usually deeper, with increased mass wasting due to freeze/thaw cycles that may occur in the higher valleys of some areas. The migration of pollutants introduced at the surface will, in most cases, be predictably downgradient in the relatively short, straight, narrow, well-defined valleys.



Setting 1 Bb West Alluvial Mtn. Valleys

Feature	Range	General Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Gravel	2	10	20
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	100-300	3	2	6

DRASTIC Index 146

Setting 1 Bb West Alluvial Mtn. Valleys

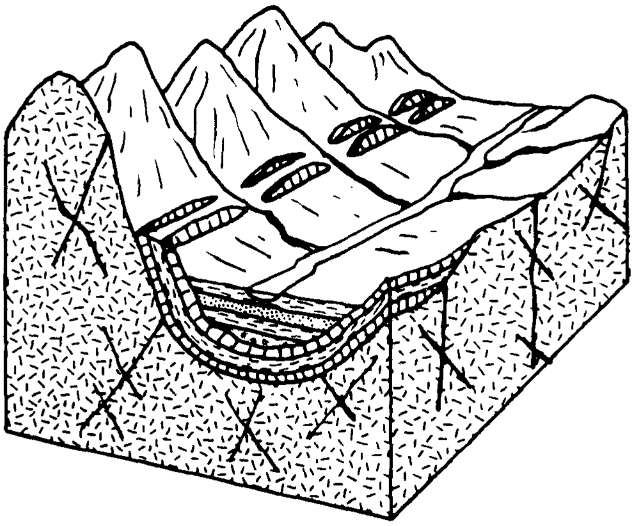
Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Gravel	5	10	50
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	100-300	2	2	4

Agricultural
DRASTIC Index 184

Western Mountain Ranges

(1Ca) Mountain Flanks—East

This hydrogeologic setting is characterized by moderate to steep topographic relief and dipping fractured consolidated sedimentary rocks, which dip toward and underlie the adjacent wide alluvial valleys. Soil cover is usually thicker than on the upper mountain slopes and typically has weathered to a sandy loam. Alluvium and/or talus deposits are not included in this setting. These sedimentary rocks, when fractured, typically have hydraulic conductivities similar to the fractured bedrock on the mountain slopes. Depth to the water table varies, but is typically deep due to lack of precipitation and moderate topographic relief, and net recharge is very low. Pollutants that may be introduced at the surface will tend to migrate most rapidly along dipping bedding planes, and through fractures.



Setting 1 Ca East Mountain Flanks

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	0-2	4	1	4
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	2	6	12
Topography	12-18%	1	3	3
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	100-300	3	2	6

DRASTIC Index 83

Setting 1 Ca East Mountain Flanks

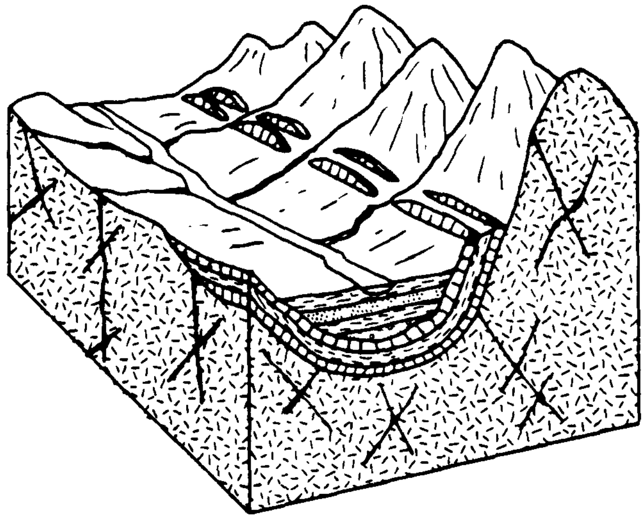
Feature	Range	Agricultural		
		Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	0-2	4	1	4
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	5	6	30
Topography	12-18%	3	3	9
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	100-300	2	2	4

Agricultural DRASTIC Index 99

Western Mountain Ranges

(1Cb) Mountain Flanks—West

This setting is similar to (1Ca) Mountain Flanks—East. Ground-water levels, however, are typically not quite as deep and ground-water recharge is greater due to the greater amount of precipitation on the western slopes. Soil depths are often greater, with more developed soil profiles. These soils are characterized by higher clay and loam content than those that occur on the eastern slopes. Analagous to the eastern flanks, any pollutants that are introduced will tend to migrate along bedding planes and fractures.



Setting 1 Cb West Mountain Flanks

Feature	Range	General Weight	General Rating	General Number
Depth to Water Table	30-50	5	5	25
Net Recharge	2-4	4	3	12
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	2	6	12
Topography	12-18%	1	3	3
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	100-300	3	2	6
		DRASTIC Index		106

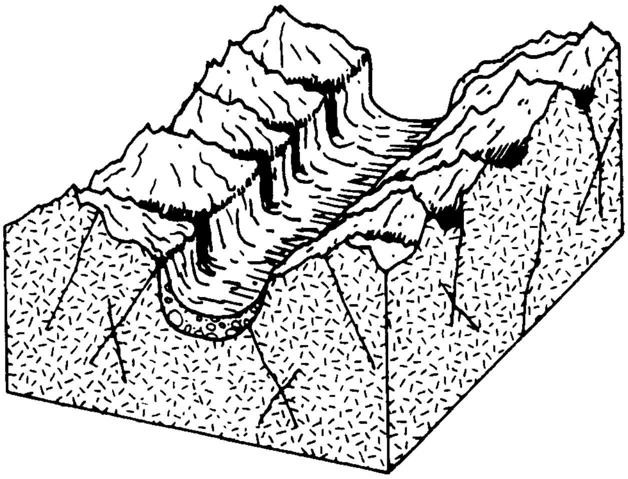
Setting 1 Cb West Mountain Flanks

Feature	Range	Agricultural Weight	Agricultural Rating	Agricultural Number
Depth to Water Table	30-50	5	5	25
Net Recharge	2-4	4	3	12
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	5	6	30
Topography	12-18%	3	3	9
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	100-300	2	2	4
		Agricultural DRASTIC Index		122

Western Mountain Ranges

(1D) Glaciated Mountain Valleys

This hydrogeologic setting is characterized by moderate topographic relief, and very coarse grained deposits associated with the near mountain glacial features, such as cirques and paternoster lakes. These deposits may serve as localized sources of water. Water tables are typically shallow with coarse grained deposits present at the surface. Mountain glaciers may be present in some areas. Although precipitation may not be great, recharge is relatively high when compared to other settings in the region because of the large volumes of water produced from the glaciers during the summer melting cycle. These recent glacial deposits are underlain by fractured bedrock of igneous or metamorphic origin all of which are in direct hydraulic connection with the overlying deposits. The fractured bedrock may also serve as a local source of ground water.



Setting 1 D Glacial Mountain Valleys

Feature	Range	General Weight	General Rating	General Number
Depth to Water Table	5-15	5	9	45
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Gravel	2	10	20
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	700-1000	3	6	18
		DRASTIC Index		180

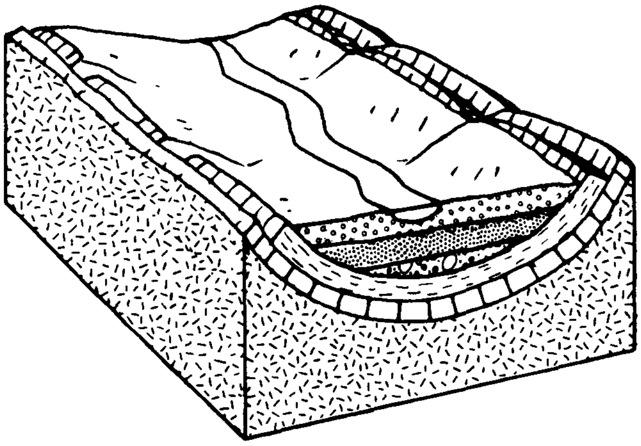
Setting 1 D Glacial Mountain Valleys

Feature	Range	Agricultural Weight	Agricultural Rating	Agricultural Number
Depth to Water Table	5-15	5	9	45
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Gravel	5	10	50
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	700-1000	2	6	12
		Agricultural DRASTIC Index		214

Western Mountain Ranges

(1Ea) Wide Alluvial Valleys (With External Drainage)—East

This hydrogeologic setting is characterized by low relief and moderately thick deposits of coarse grained alluvium deposited by water. It is similar to Narrow Alluvial Valleys except that the valleys are better developed and the streams which occupy their channels have a shallower gradient. Typically the alluvial deposits are finer grained and thicker than the Narrow Alluvial Valleys. The alluvium in this setting serves as the major source of ground water and is often capable of supplying large quantities of water. Surficial deposits are usually coarse grained and water levels are relatively shallow even though precipitation and net recharge are low. The alluvium is underlain by layers of permeable sedimentary rock which receive their primary source of recharge from the adjacent mountain flanks. The sedimentary sequence is underlain by fractured bedrock of igneous or metamorphic origin. Ground water may also be obtained from the permeable sedimentary rocks.



Setting 1 Ea East Wide Alluvial Valleys (External Drainage)

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Gravel	2	10	20
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	700-1000	3	6	18
		DRASTIC Index		158

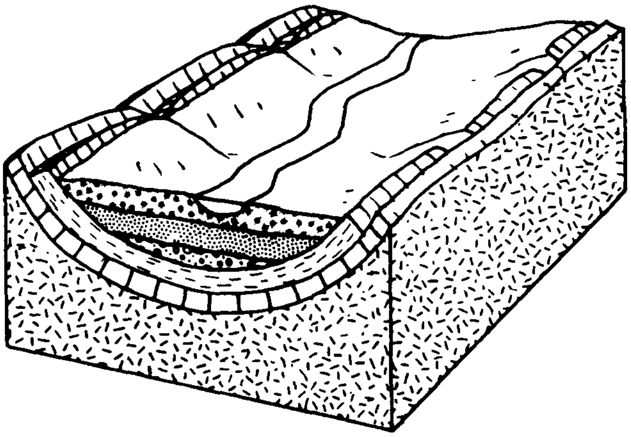
Setting 1 Ea East Wide Alluvial Valleys (External Drainage)

Feature	Range	Agricultural		
		Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Gravel	5	10	50
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	700-1000	2	6	12
		Agricultural DRASTIC Index		192

Western Mountain Ranges

(1Eb) Wide Alluvial Valleys (External Drainage)—West

This setting is similar to (1Ea) Wide Alluvial Valleys (External Drainage)—East except that water levels are typically shallow because of higher precipitation and greater ground-water recharge. Soils tend to be better developed and thicker in the areas bordering the mountain flanks (1Cb), however, in the valley lowlands, gravelly soils predominate. Pollutants introduced at the surface in these wide alluvial valleys tend to migrate rapidly in the coarser grained deposits and travel into and along fracture planes.



Setting 1 Eb West Wide Alluvial Valleys (External Drainage)

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Gravel	2	10	20
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	700-1000	3	6	18

DRASTIC Index 180

Setting 1 Eb West Wide Alluvial Valleys (External Drainage)

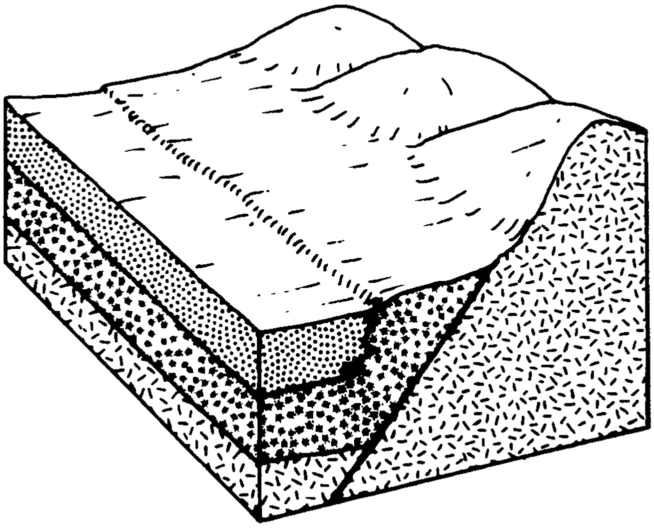
		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Gravel	5	10	50
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	700-1000	2	6	12

Agricultural DRASTIC Index 214

Western Mountain Ranges

(1F) Coastal Beaches

This hydrogeologic setting is characterized by low topographic relief, near sea level elevation and sandy surface soils. These areas have very high potential infiltration rates. These areas are commonly ground water discharge areas, which, when utilized for fresh water supply, are quickly endangered by salt-water intrusion. Due to their very permeable nature and thin vadose zone, they are very vulnerable to pollution. Under natural gradients, pollution of this zone is usually discharged to the sea. However, with inland pumping, flow is rapidly reversed to the pumping center.



Setting 1 F Coastal Beaches

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	0-5	5	10	50
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	0-2%	1	10	10
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	700-1000	3	6	18

DRASTIC Index 196

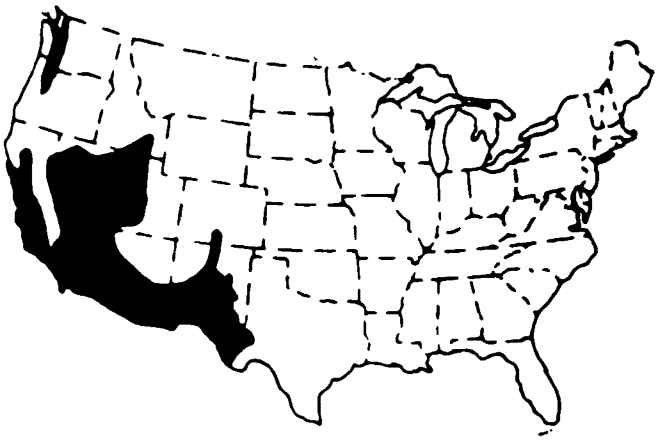
Setting 1 F Coastal Beaches

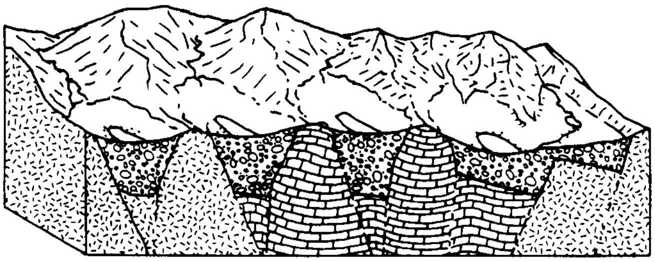
		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	0-5	5	10	50
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	0-2%	3	10	30
Impact Vadose Zone	Sand and Gravel	4	8	24
Hydraulic Conductivity	700-1000	2	6	12

Agricultural DRASTIC Index 221

2. *Alluvial Basins*

(Thick alluvial deposits in basins and valleys bordered by mountains and locally of glacial origin)





The Alluvial Basins region occupies a discontinuous area of 1,025,000 km^2 extending from the Puget Sound-Willamette Valley area of Washington and Oregon to west Texas. The region consists of an irregular alternation of basins or valleys and mountain ranges. From the standpoint of topography, it is useful to contrast this region with the Western Mountain Ranges. In the Western Mountain Ranges the high areas, the mountains, are the dominant feature. In the Alluvial Basins region the low areas, the basins and valleys, are the dominant feature. The principal exception to this generalization is the Coast Ranges of southern California which, though included in this region, topographically more closely resemble the Western Mountain Ranges.

Most of the Nevada and all of the Utah parts of this region are an area of internal drainage referred to as the Great Basin. No surface or subsurface flow leaves this part of the region, and all water reaching it from adjacent areas and from precipitation is returned to the atmosphere by evaporation or by the transpiration of plants.

The basins and valleys are diverse in size, shape, and altitude. They range in altitude from about 85 m below sea level in Death Valley in California to 2,000 m above sea level in the San Luis Valley in Colorado. The basins range in size from a few hundred meters in width and a kilometer or two in length to, for the Central Valley of California, as much as 80 km in width and 650 km in length. The crests of the mountains are commonly 1,000 to 1,500 m above the adjacent valley floors.

The surrounding mountains, and the bedrock beneath the basins, consist of granite and metamorphic rocks of Precambrian to Tertiary age and consolidated sedimentary rocks of Paleozoic to Cenozoic age. The rocks are broken along fractures and faults that may serve as water-bearing openings. However, the openings in the granitic and metamorphic rocks in the mountainous area have a relatively small capacity to store and to transmit ground water.

The dominant element in the hydrology of the region is the thick (several hundred to several thousand meters) layer of generally unconsolidated alluvial material that partially fills the basins. Except for the part of the region in Washington and Oregon, the material was derived from erosion of the adjacent mountains and was transported down steep-gradient streams into the basins where it was deposited as alluvial fans. Generally, the coarsest material in an alluvial fan occurs at its apex, adjacent to the mountains; the material gets progressively finer toward the center of the basins. In time, the fans formed by adjacent streams coalesced to form a continuous and thick deposit of alluvium that slopes gently from the mountains toward the center of the basins. These alluvial-fan deposits are overlain by or grade into fine-grained flood plain, lake, or playa deposits in the central part of most basins. The fine-grained deposits are especially suited to large-scale cultivation.

The Puget Sound and Willamette Valley areas differ geologically from the remainder of the region. The

Puget Sound area is underlain by thick and very permeable deposits of gravel and sand laid down by streams of glacial meltwater derived from ice tongues that invaded the area from the north during the Pleistocene. The gravel and sand are interbedded with clay in parts of the area. The Willamette Valley is mostly underlain by interbedded sand, silt and clay deposited on floodplains by the Willamette River and other streams.

The Alluvial Basins region is the driest area in the United States, with large parts of it being classified as semiarid and arid. Annual precipitation in the valleys in Nevada and Arizona ranges from about 100 to 400 mm. However, in the mountainous areas throughout the region, in the northern part of the Central Valley of California, and in the Washington-Oregon area, annual precipitation ranges from about 400 mm to more than 800 mm. The region also receives runoff from streams that originate in the mountains of the Western Mountain Ranges region.

Because of the very thin cover of unconsolidated material on the mountains in the Alluvial Basins region, precipitation runs off rapidly down the valleys and out onto the fans where it infiltrates into the alluvium. The water moves through the sand and gravel layers toward the centers of the basins. The centers of many basins consist of flat-floored, vegetation-free areas onto which ground water may discharge and on which overland runoff may collect during intense storms. The water that collects in these areas, which are called playas, evaporates relatively quickly, leaving both a thin deposit of clay and other sediment transported by overland runoff and a crust consisting of the soluble salts that were dissolved in the water.

Studies in the region have shown that the hydrology of the Alluvial Basins is more complex than that described in the preceding paragraph, which applies only to what has been described as "undrained closed basins." Water may move through permeable bedrock from one basin to another, arriving, ultimately, at a large playa referred to as a "sink" into the ground, as the name might imply, but by evaporating, as in other playas. In those parts of the Alluvial Basin region drained by perennial streams, including the Puget Sound-Willamette Valley area, the Central Valley of California, and some of the valleys in Arizona and New Mexico, ground-water discharges to the streams from the alluvial deposits. However, before entering the streams, water may move down some valleys through the alluvial deposits for tens of kilometers. A reversal of this situation occurs along the lower Colorado River and at the upstream end of the valleys of some of the other perennial streams; in these areas, water moves from the streams into the alluvium to supply the needs of the adjacent vegetated zones.

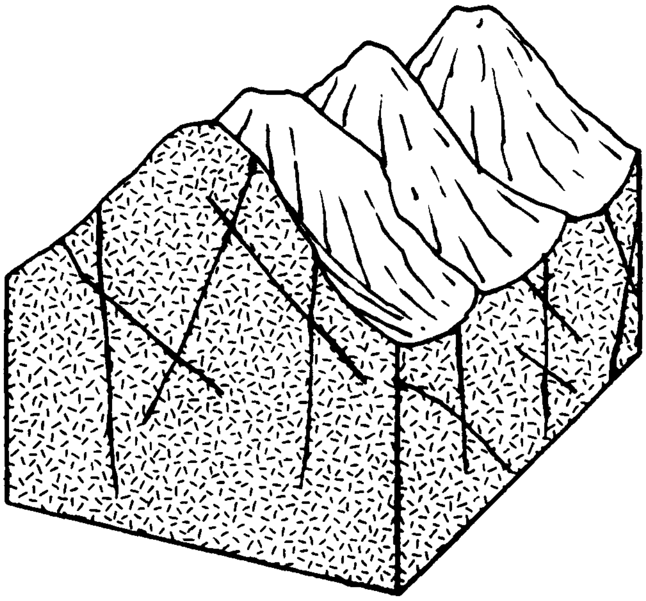
Ground water is the major source of water in the Alluvial Basins region. Many of the valleys in this region have been developed for agriculture. Because of the dry climate, agriculture requires intensive irrigation. In the part of this region drained by the Colorado River, ground water used for irrigation in 1975 amounted to about 6 billion cubic meters (4,864,000 acre-feet). Most of the ground water is obtained from wells drawing from the sand and gravel deposits in the valley alluvium. These deposits are interbedded with finer grained layers of silt and clay that are also saturated with water. When hydraulic heads in the sand and gravel layers are lowered by withdrawals, the water in the silt and clay begins to move slowly into the sand and gravel. The movement, which in some areas takes decades to become significant, is accompanied by compaction of the silt and clay and subsidence of the land surface. Subsidence is most severe in parts of the Central Valley, where it exceeds 9 m in one area, and in southern Arizona, where subsidence of more than 4 m has been observed.

In both the Alluvial Basins and the Colorado Plateau regions, large volumes of water are transpired by phreatophytes (water-loving plants) of small economic value that live along streams and in other wet areas. In an effort to increase the amount of water available for irrigation and other uses, numerous studies have been made to determine the volumes of water used by phreatophytes and to devise means to control them. A few small control efforts have been made, but none have proven economically effective.

Alluvial Basins

(2A) Mountain Slopes

This hydrogeologic setting is characterized by steep slopes on the side of mountains, a thin soil cover and highly fractured bedrock. Ground water is obtained primarily from the fractures in the bedrock which may be of sedimentary, metamorphic or igneous origin. The fractures provide only localized sources of ground water and well yields are typically limited even though the hydraulic conductivity may be high because of the fractures. Due to the steep slopes, thin soil cover and small storage capacity of the fractures, runoff is significant and ground-water recharge is minimal. Ground-water levels are extremely variable, but are typically deep.



Setting 2 A Mountain Slopes

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	50-75	5	3	15
Net Recharge	0-2	4	1	4
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	2	10	20
Topography	12-18%	1	3	3
Impact Vadose Zone	Metamorphic/ Igneous	5	4	20
Hydraulic Conductivity	1-100	3	1	3

DRASTIC Index 74

Setting 2 A Mountain Slopes

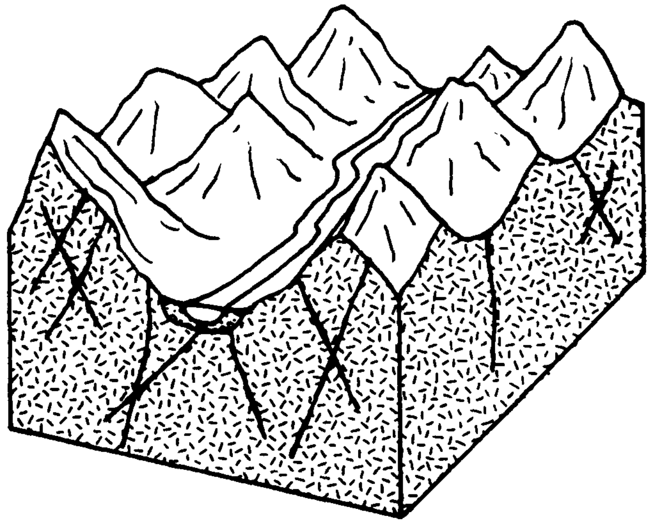
Feature	Range	Agricultural		
		Weight	Rating	Number
Depth to Water Table	50-75	5	3	15
Net Recharge	0-2	4	1	4
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	5	10	50
Topography	12-18%	3	3	9
Impact Vadose Zone	Metamorphic/ Igneous	4	4	16
Hydraulic Conductivity	1-100	2	1	2

Agricultural
DRASTIC Index 105

Alluvial Basins

(2B) Alluvial Mountain Valleys

This hydrogeologic setting is characterized by thin bouldery alluvium which overlies fractured bedrock of sedimentary, metamorphic or igneous origin. Slopes in the valley typically range from 2-6%. The alluvium, which is derived from the surrounding steep slopes serves as a localized source of water. Water levels are moderate in depth, but because of the low rainfall, ground-water recharge is low. Ground water may also be obtained from the fractures in the underlying bedrock which are typically in direct hydraulic connection with the overlying alluvium.



Setting 2 B Alluvial Mountain Valleys

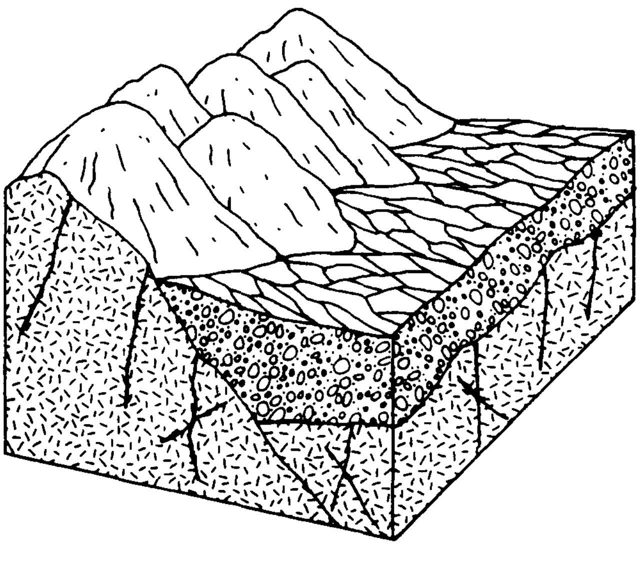
Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	300-700	3	4	12

DRASTIC Index 132

Setting 2 B Alluvial Mountain Valleys

Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	300-700	2	4	8

Agricultural DRASTIC Index 165



Alluvial Basins

(2C) Alluvial Fans

This hydrogeologic setting is characterized by gently sloping alluvial deposits which are coarser near the apex in the mountains and grade toward finer deposits in the basins. Within the alluvial deposits are layers of sand and gravel which extend into the central parts of the adjacent basins. The alluvial fans serve as local sources of water and also as the recharge area for the deposits in the adjacent basin. The portion of the fan extending farthest into the basin may function as a discharge area, especially during seasons when the upper portion of the fan is receiving substantial recharge. Discharge zones are usually related to flow along the top of stratified clay layers. Ground water discharge zones are less vulnerable to pollution than recharge zones. Where the discharge/recharge relationship is reversible the greater vulnerability of the recharge condition must be evaluated. Ground-water levels are extremely variable, and the quantity of water available is limited because of the low precipitation and low net recharge. Ground-water depth varies from over 100 feet near the mountains to zero in the discharge areas. The alluvial fans are underlain by fractured bedrock of sedimentary, metamorphic or igneous origin which are typically in direct hydraulic connection with the overlying deposits. Limited supplies of ground water are available from the fractures in the bedrock.

Setting 2 C Alluvial Fans

Feature	Range	General Weight	Rating	Number
Depth to Water Table	50-75	5	3	15
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	300-700	3	4	12

DRASTIC Index 122

Setting 2 C Alluvial Fans

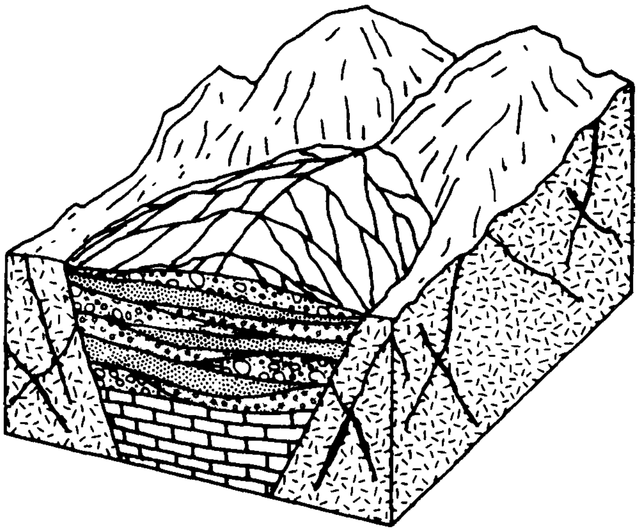
Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	50-75	5	3	15
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	300-700	2	4	8

Agricultural DRASTIC Index 155

Alluvial Basins

(2D) Alluvial Basins (Internal Drainage)

This hydrogeologic setting is characterized by low topographic relief and thick deposits of unconsolidated alluvial material formed by coalescing alluvial fans. The sand and gravel deposits within the alluvium are the major source of water in the region. The sand and gravel is interbedded with finer grained layers of saturated clay and silt which serve as a source of recharge to the sand and gravel when head differences are significant. The alluvium is underlain by fractured igneous or metamorphic rocks and consolidated sedimentary rocks. Although some of the sedimentary rocks are permeable and water may be obtained from fractures in the crystalline bedrock, the abundance of water in the alluvium and the greater depth of the bedrock serves to minimize use of these sources. Since these basins have internal drainage, natural gradients are low near the basin centers. Thus, the primary direction of pollutant migration, under normal conditions, would be downward, and outward radially from the point of incidence.



Setting 2 D Alluvial Basins (Internal Drainage)

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	2-6%	1	9	9
Impact Vadose Zone	S & G w/sig. Silt and Clay	5	6	30
Hydraulic Conductivity	300-700	3	4	12

DRASTIC Index 122

Setting 2 D Alluvial Basins (Internal Drainage)

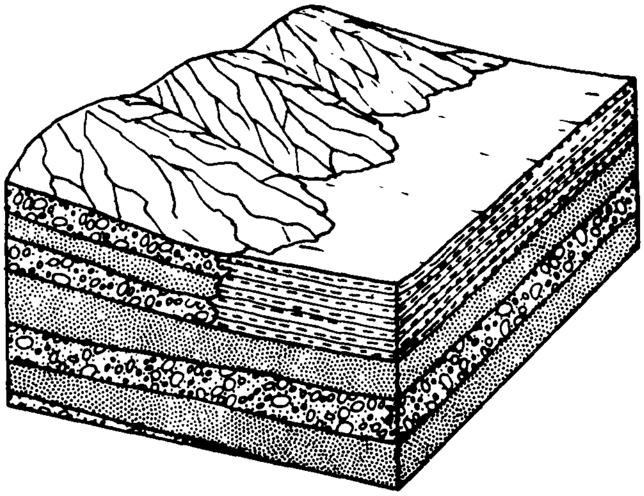
		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	2-6%	3	9	27
Impact Vadose Zone	S & G w/sig Silt and Clay	4	6	24
Hydraulic Conductivity	300-700	2	4	8

Agricultural DRASTIC Index 157

Alluvial Basins

(2E) Playa Lakes

This hydrogeologic setting is characterized by very low topographic relief and thin layers of clays and other fine grained sediments which overlie alluvial deposits. The playa areas serve as a catchment for water during periods of significant runoff; when the precipitation event is over, the water evaporates, leaving a crust of soluble salts on the surface. Ground water is obtained from the layers of sand which underly the finer-grained deposits. Water levels are extremely variable but are typically deep. The playa beds are significant recharge areas due to the ground-water "mounding" that occurs seasonally beneath the playas. The rate of recharge, as compared to evaporation, is largely a function of the permeability of the materials forming the bed of the playa, and the distribution, in time, of precipitation.



Setting 2 E Playa Lakes

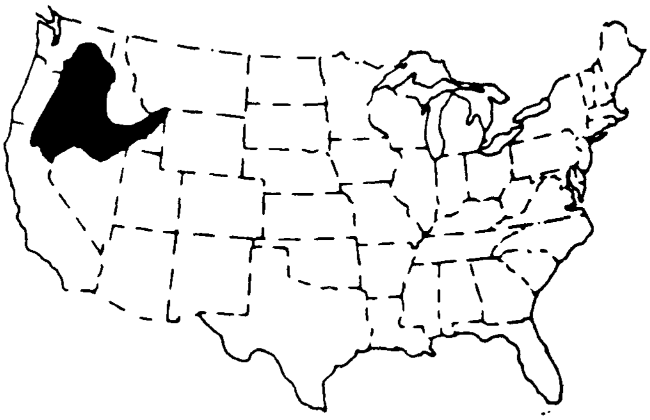
Feature	Range	General Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Shrink/Agg. Clay	2	7	14
Topography	0-2%	1	10	10
Impact Vadose Zone	S & G w/sig. Silt and Clay	5	6	30
Hydraulic Conductivity	700-1000	3	6	18
		DRASTIC Index		110

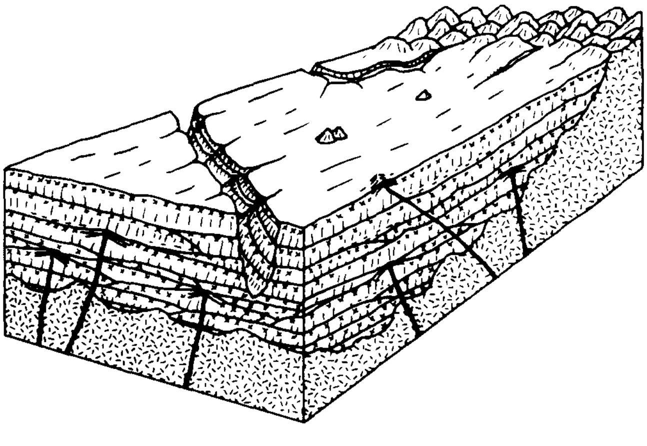
Setting 2 E Playa Lakes

Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Shrink/Agg. Clay	5	7	35
Topography	0-2%	3	10	30
Impact Vadose Zone	S & G w/sig. Silt and Clay	4	6	24
Hydraulic Conductivity	700-1000	2	6	12
		Agricultural DRASTIC Index		139

3. *Columbia Lava Plateau*

(Thick sequence of lava flows irregularly interbedded with thin unconsolidated deposits and overlain by thin soils)





The Columbia Lava Plateau occupies an area of 366,000 km^2 in northeastern California, eastern Washington and Oregon, southern Idaho, and northern Nevada. As its name implies, it is basically a plateau standing at an altitude generally between 500 and 1,800 m above sea level that is underlain by a great thickness of lava flows irregularly interbedded with silt, sand, and other unconsolidated deposits. The plateau is bordered on the west by the Cascade Range, on the north by the Okanogan Highlands, and on the east by the Rocky Mountains. On the south it grades into the Alluvial Basins regoin, as the area occupied by lava flows decreases and the typical "basin and range" topography of the Alluvial Basins region gradually prevails. Most of the plateau in Idaho is exceptionally flat over large areas, the principal relief being low cinder (volcanic) cones and lava domes. This area and much of the area in California, southeastern Oregon, and Nevada is underlain by much of the youngest lava, some of which is less than 1,000 years old. In Washington the flows are older, some dating back to the Miocene Epoch. Altitudes in a few of the mountainous areas in the plateau region exceed 3,000 m.

The great sequence of lava flows, which ranges in thickness from less than 50 m adjacent to the bordering mountain ranges to more than 1,000 m in south-central Washington and southern Idaho, is the principal water-bearing unit in the region. The water-bearing lava is underlain by granite, metamorphic rocks, older lava flows, and sedimentary rocks, none of which are very permeable. Individual lava flows in the water-bearing zone range in thickness from several meters to more than 50 m and average about 15 m. Most of the lava is basalt which reached the surface both through extensive fissures and through local eruption centers. Because basaltic lava is very fluid when molten, it flows considerable distances down surface depressions and over gently sloping surfaces and forms, when it solidifies, a relatively flat surface. Some flows are sheetlike and can be followed visually for several kilometers along the walls of steep canyons. Other flows, where the lava issuing from eruption centers followed surface depressions, are lobate, or tonguelike.

The volcanic rocks yield water mainly from permeable zones that occur at or near the contacts between some flow layers. The origin of these flow-contact or interflow zones is complex but involves, among other causes, the relatively rapid cooling of the top of flows, which results in formation of a crust. As the molten lava beneath continues to flow, the crust may be broken into a rubble of angular fragments which in places contain numerous holes where gas bubbles formed and which give the rock the appearance of a frozen froth. The slower cooling of the central and lower parts of the thicker flows results in a dense, flint-like rock which in the lower part contains relatively widely spaced, irregular fractures and which grade upward into a zone containing relatively closely spaced vertical fractures that break the rock into a series of hexagonal columns (Newcomb, 1961).

Periods of time ranging from less than 100 years to thousands of years elapsed between extrusion of successive lava flows. As a result, parts of some flows are separated by soil zones and, at places, by sand, silt, and clay deposited by streams or in lakes that existed on the land surface before being buried by subsequent lava extrusions. These sedimentary layers, where they occur between lava flows, are commonly referred to as "interflow sediments." Gravel, sand, silt, and clay, partly formed by the present streams and partly of glacial origin, cover the volcanic rocks and the older exposed bedrock in parts of the area.

From the standpoint of the hydraulic characteristics of the volcanic rocks, it is useful to divide the Columbia Lava Plateau region into two parts: (1) the area in southeastern Washington, northeastern Oregon, and the Lewiston area of Idaho, part of which is underlain by volcanic rocks of the Columbia River Group; and (2) the remainder of the area, which also includes the Snake River Plain. The basalt underlying the Snake River Plain is referred to as the Snake River Basalt; that underlying southeastern Oregon and the remainder of this area has been divided into several units, to which names of local origin are applied (Hampton, 1964).

The Columbia River Group is of Miocene to Pliocene age and consists of relatively thick flows that have been deformed into a series of broad folds and offset locally along normal faults. Movement of ground water occurs primarily through the interflow zones near the top of flows and, to a much smaller extent, through fault zones and through joints developed in the dense central and lower parts of the flows. The axes of sharp folds and the offset of the interflow zones along faults form subsurface dams that affect the movement of ground water. Water reaching the interflow zones tends to move down the dip of the flows from fold axes and to collect undip behind faults that are transverse to the direction of movement (Newcomb, 1961). As a result, the basalt in parts of the area is divided into a series of barrier-controlled reservoirs which are only poorly connected hydraulically to adjacent reservoirs.

The water-bearing basalt underlying California, Nevada, southeastern Oregon, and southern Idaho is of Pliocene to Holocene age and consists of small, relatively thin flows that have been affected to a much smaller extent by folding and faulting than has the Columbia River Group. The thin flows contain extensive, highly permeable interflow zones that are relatively effectively interconnected through a dense network of cooling fractures. Structural barriers to ground-water movement, such as those of the Columbia River Group, are of minor importance. This is demonstrated by conditions in the 44,000-square-kilometer area of the Snake River Plain east of Bliss, Idaho, which Nace (1958) thought might be the largest unified ground-water reservoir on the North American continent. (It is probable that this distinction is held by the Floridan aquifer, which underlies an area of 212,000 km^2 in Alabama, Florida, Georgia, and South Carolina. See region 11).

The interflow zones form a complex sequence of relatively horizontal aquifers that are separated vertically by the dense central and lower parts of the lava flows and by interlayered clay and silt. Hydrologists estimate that the interflow zones, which range in thickness from about 1 m to about 8 m, account for about 10 percent of the basalt. MacNish and Barker (1976) have estimated, on the basis of studies in the Walla Walla River basin in Washington and Oregon, that the hydraulic conductivity along the flow-contact zones may be a billion times larger than the hydraulic conductivity across the dense zones. The lateral extent of individual aquifers depends on the area covered by the different lava flows, on the presence of dikes and other igneous intrusions, and on faults and folds that terminate the porous zones, especially in the Columbia River Group.

The large differences in hydraulic conductivity between aquifers and the intervening "confining zones" result in significant differences in hydraulic heads between different aquifers. These differences reflect the head losses that occur as water moves vertically through the system. As a result, heads decrease with increasing depth in recharge areas and increase with increasing depth near the streams that serve as major lines of ground-water discharge. The difference in heads between different aquifers can result in the movement of large volumes of water between aquifers through the open-hole (uncased) sections of wells.

Much of the Columbia Lava Plateau region is in the "rain shadow" east of the Cascades and, as a result, receives only 200 to 1,200 mm of precipitation annually. The areas that receive the least precipitation include the plateau area immediately east of the Cascades and the Snake River Plain. The areas that receive the largest amounts of precipitation include the east flank of the Cascades and the areas adjacent to the Okanogan Highlands and the Rocky Mountains. Recharge to the ground-water system depends on several factors, including the amount and seasonal distribution of precipitation and the permeability of the surficial materials. Most precipitation occurs in the winter and thus coincides with the cooler, nongrowing season when conditions are most favorable for recharge. Mundorff (Columbia-North Pacific Technical Staff, 1970) estimates that recharge may amount to 600 mm in areas underlain by highly permeable young lavas that receive abundant precipitation. Considerable recharge also occurs by infiltration of water from streams that flow onto the plateau from the adjoining mountains. These sources of natural recharge are supplemented in agricultural areas by the infiltration of irrigation water.

Discharge from the ground-water system occurs as seepage to streams, as spring flow, and by evapotranspiration in areas where the water table is at or near the land surface. The famous Thousand Springs and other springs along the Snake River canyon in southern Idaho are, in fact, among the most spectacular displays of ground-water discharge in the world.

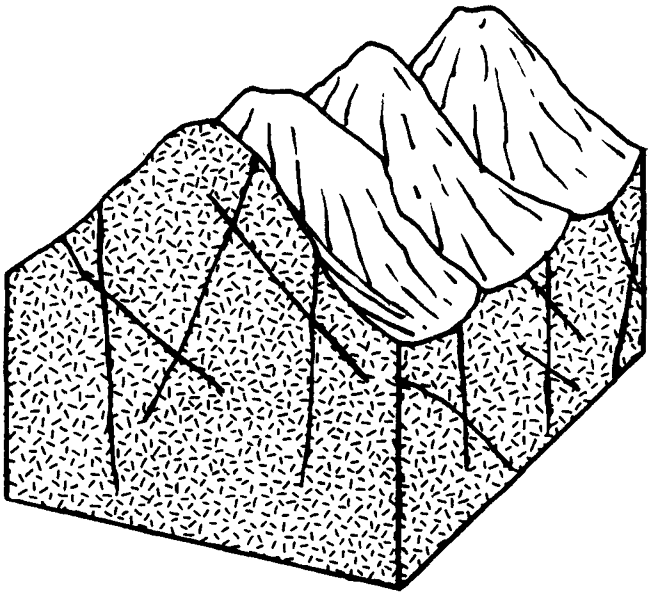
The Columbia Lava Plateau region is mantled by mostly thin soils developed on alluvial and wind-laid deposits that are well suited for agriculture. Because of the arid and semiarid climate in most of the region, many crops require intensive irrigation. In 1970, for example, more than 15,000 km^2 (3.75 million acres) were being irrigated on the Snake River Plain. Water for irrigation is obtained both by diversions from streams and by wells that tap the lava interflow zones. Much of the water applied for irrigation percolates downward into the lava and then moves through the ground-water system to the Columbia and Snake Rivers and to other streams that have deeply entrenched channels. The effect of this "return flow" is graphically indicated by a long-term increase in the flow of the Thousand Springs and other large springs along the Snake River gorge between Milner and King Hill—from about 110 m^3 sec^{-1} in 1902, prior to significant irrigation, to more than 225 m^3 sec^{-1} by 1942, after decades of irrigation on adjacent and upstream parts of the plateau. Prior to the start of irrigation, the water represented by this increased flow reached the Snake River below King Hill through tributary streams and natural ground-water discharge.

The large withdrawal of water in the Columbia Lava Plateau for irrigation, industrial, and other uses has resulted in declines in ground-water levels of as much as 30 to 60 m in several areas. In most of these areas, the declines have been slowed or stopped through regulatory restrictions or other changes that have reduced withdrawals. Declines are still occurring, at rates as much as a few meters per year, in a few areas.

Columbia Lava Plateau

(3A) Mountain Slopes

This hydrogeologic setting is characterized by steep slopes on the side of mountains bordering the plateau, a thin soil cover and fractured bedrock. Steep slopes also occur on cinder cones within the plateau. Ground water is obtained primarily from the fractures in the bedrock which may be sedimentary, metamorphic or igneous origin. The fractures provide localized sources of ground water and well yields are typically limited. Due to the thin soil cover, topography, and small storage capacity of the fractures, runoff is significant. Ground-water levels are extremely variable but are typically deep. Due to lack of rainfall, low hydraulic conductivity, and steep topography, net recharge is very low.



Setting 3 A Mountain Slopes

			General	
Feature	Range	Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	2-4	4	3	12
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	2	10	20
Topography	12-18%	1	3	3
Impact Vadose Zone	Metamorphic/ Igneous	5	4	20
Hydraulic Conductivity	1000-2000	3	8	24

DRASTIC Index 98

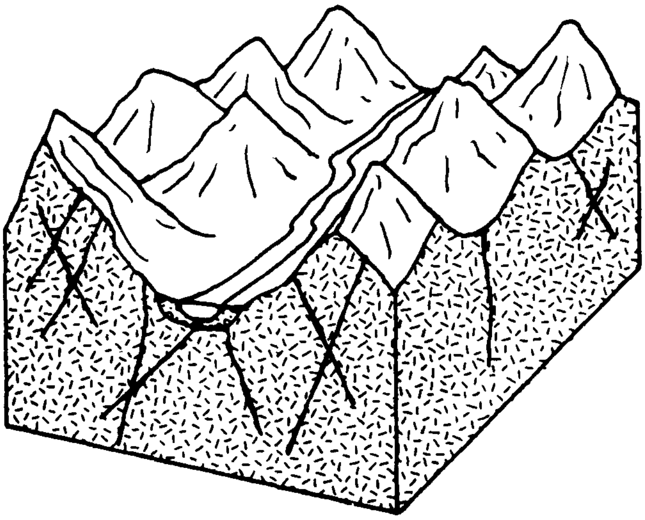
Setting 3 A Mountain Slopes

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	2-4	4	3	12
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	5	10	50
Topography	12-18%	3	3	9
Impact Vadose Zone	Metamorphic/ Igneous	4	4	16
Hydraulic Conductivity	1000-2000	2	8	16
		Agricultural DRASTIC Index		122

Columbia Lava Plateau

(3B) Alluvial Mountain Valleys

This hydrogeologic setting is characterized by thin bouldery alluvium which overlies fractured bedrock of sedimentary, metamorphic or igneous origin. The alluvium, which is derived from the surrounding steep slopes serves as a localized source of water. Water levels are typically moderate and recharge to the ground water may be of significance. Ground water may also be obtained from the fractures in the underlying bedrock which are typically in direct hydraulic connection with the overlying alluvium.



Setting 3 B Alluvial Mountain Valleys

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Gravel	2	10	20
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	700-1000	3	6	18
		DRASTIC Index		168

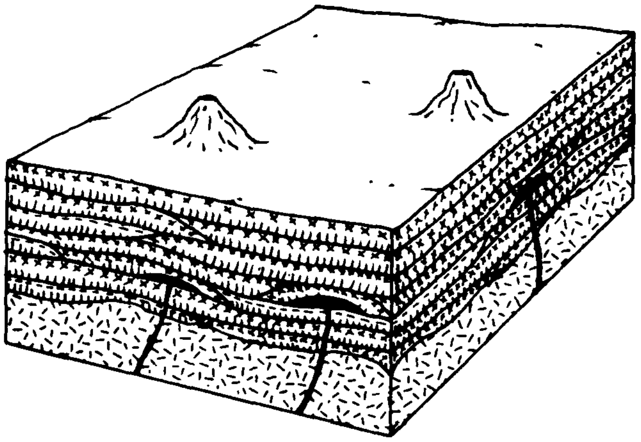
Setting 3 B Alluvial Mountain Valleys

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Gravel	5	10	50
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	700-1000	2	6	12
		Agricultural DRASTIC Index		202

Columbia Lava Plateau

(3C) Hydraulically Connected Lava Flows

This hydrogeologic setting is characterized by low topographic relief, a thin sandy soil cover and a thick sequence of successive lava flows which is irregularly interbedded with thin unconsolidated deposits. The lava beds are underlain by poorly-permeable bedrock of igneous, sedimentary or metamorphic origin. Ground water is obtained primarily from the interflow zones comprised of sequential, thin, lava flows and related sedimentary deposits, cooling fractures, lava tubes, and minor structural features. Water levels are extremely variable but are typically deep. Well yields may vary from low to extremely high depending on the characteristics of the underlying lava flows at a particular site. Ground-water recharge may be appreciable because the layers of lava are interconnected hydraulically. This setting is characterized by the deposits that occur in southwestern Idaho (Snake River area), northern Nevada, southeastern Oregon, and extreme northeastern California, which are of Pliocene to Holocene age.



Setting 3 C Hydraulically Connected Lava Flows

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	50-75	5	3	15
Net Recharge	2-4	4	3	12
Aquifer Media	Basalt	3	9	27
Soil Media	Sand	2	9	18
Topography	2-6%	1	9	9
Impact Vadose Zone	Basalt	5	9	45
Hydraulic Conductivity	2000+	3	10	30

DRASTIC Index 156

Setting 3 C Hydraulically Connected Lava Flows

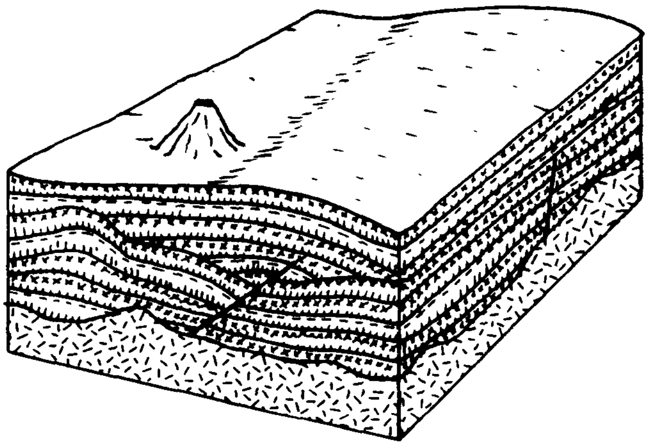
Feature	Range	Agricultural		
		Weight	Rating	Number
Depth to Water Table	50-75	5	3	15
Net Recharge	2-4	4	3	12
Aquifer Media	Basalt	3	9	27
Soil Media	Sand	5	9	45
Topography	2-6%	3	9	27
Impact Vadose Zone	Basalt	4	9	36
Hydraulic Conductivity	2000+	2	10	20

Agricultural
DRASTIC Index 182

Columbia Lava Plateau

(3D) Lava Flows Not Connected Hydraulically

This hydrogeologic setting is characterized by low topographic relief, a thin cover of gravel, sand, silt, and clay of stream and glacial origin and a sequence of thick lava flows irregularly interbedded with unconsolidated deposits, which have been deformed into a series of folds and normal faults. The lava sequence is underlain by poorly-permeable bedrock of igneous, sedimentary, or metamorphic origin. Ground water is obtained primarily from the interflow zones of sedimentary deposits and cooling fractures which occur between successive layers of lava. Water levels are extremely variable, but are typically deep. The presence of thick impermeable zones may produce perched water-table conditions or disrupt the hydraulic continuity of water bearing zones. The flow of ground water is controlled by locally offset normal faults which form a series of hydraulically poorly-connected reservoirs. This setting is characterized by deposits that occur in the Columbia River area in southern Washington, northern Oregon, and northern Idaho which are Miocene to Pliocene (?) in age.



Setting 3 D Lava Flows Not Connected Hydraulically

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	50-75	5	3	15
Net Recharge	2-4	4	3	12
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sand	2	9	18
Topography	2-6%	1	9	9
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	1-100	3	1	3

DRASTIC Index 105

Setting 3 D Lava Flows Not Connected Hydraulically

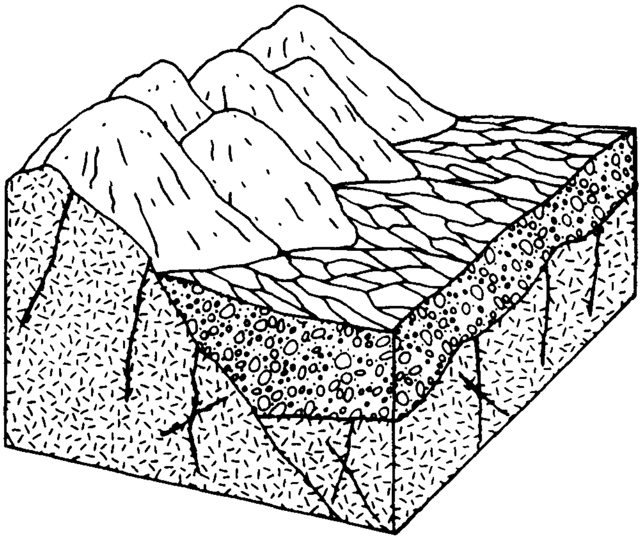
Feature	Range	Agricultural		
		Weight	Rating	Number
Depth to Water Table	50-75	5	3	15
Net Recharge	2-4	4	3	12
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sand	5	9	45
Topography	2-6%	3	9	27
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	1-100	2	1	2

Agricultural DRASTIC Index 143

Columbia Lava Plateau

(3E) Alluvial Fans

This hydrogeologic setting is characterized by alluvial sediments which are thickest near the mountain slopes and thin toward the interior basin. Topography is steep to moderate. Fan sediments range from coarse, unsorted debris on the upper slopes grading to well-sorted and stratified gravels, sands, and clays. Recharge is a function of precipitation and evaporation, since the permeability of the surface materials is usually high. Ground-water movement is generally unidirectional from the adjacent highlands toward the basin. Depth to ground water is generally moderate to deep. These fans may serve as local sources of water and also as the recharge area for the deposits in the adjacent basin and the lower extremities may serve as discharge areas to local streams.



Setting 3 E Alluvial Fans

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	6-12%	1	5	5
Impact Vadose Zone	S & G w/sig Silt and Clay	5	6	30
Hydraulic Conductivity	300-700	3	4	12

DRASTIC Index 105

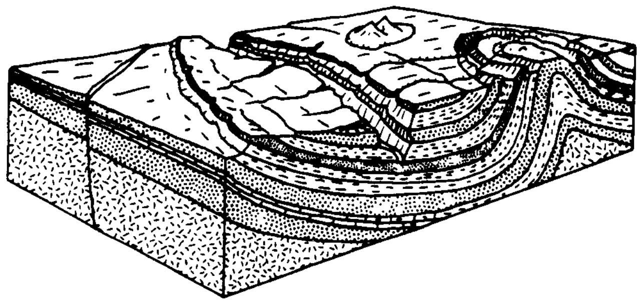
Setting 3 E Alluvial Fans

Feature	Range	Agricultural		
		Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	6-12%	3	5	15
Impact Vadose Zone	S & G w/sig Silt and Clay	4	6	24
Hydraulic Conductivity	300-700	2	4	8

Agricultural DRASTIC Index 123

4. *Colorado Plateau and Wyoming Basin*

(Thin soils over consolidated sedimentary rocks)



The Colorado Plateau and Wyoming Basin region occupies an area of 414,000 km^2 in Arizona, Colorado, New Mexico, Utah, and Wyoming. It is a region of canyons and cliffs; of thin, patchy, rocky soils; and of sparse vegetation adapted to the arid and semiarid climate. The large-scale structure of the region is that of a broad plateau standing at an altitude of 2,500 to 3,500 m and underlain by essentially horizontal to gently dipping layers of consolidated sedimentary rocks. The plateau structure has been modified by an irregular alternation of basins and domes, in some of which major faults have caused significant offset of the rock layers.

The region is bordered on the east, north, and west by mountain ranges that tend to obscure its plateau structure. The northern part of the region—the part occupied by the Wyoming Basin—borders the Nonglaciated Central region at the break in the Rocky Mountains between the Laramie Range and the Bighorn Mountains. The region contains small, isolated mountain ranges, the most prominent being the Henry Mountains and the La Sal Mountains in southeastern Utah. It also contains, rather widely scattered over the region, extinct volcanoes and lava fields, the most prominent example being the San Francisco Mountains in north-central Arizona.

The rocks that underlie the region consist principally of sandstone, shale, and limestone of Paleozoic to Cenozoic age. In parts of the region these rock units include significant amounts of gypsum (calcium sulfate). In the Paradox Basin in western Colorado the rock units include thick deposits of sodium- and potassium-bearing minerals, principally halite (sodium chloride). The sandstones and shales are most prevalent and most extensive in occurrence. The sandstones are the principal sources of ground water in the region and contain water in fractures developed both along bedding planes and across the beds and in interconnected pores. The most productive sandstones are those in which calcium carbonate or other cementing material has been deposited only around the point of contact of the sand grains. Thus, many of the sandstones are only partially cemented and retain significant primary porosity.

Unconsolidated deposits are of relatively minor importance in this region. Thin deposits of alluvium capable of yielding small to moderate supplies of ground water occur along parts of the valleys of major streams, especially adjacent to the mountain ranges in the northern and eastern parts of the region. These deposits are partly of glacial origin. In most of the remainder of the region there are large expanses of exposed bedrock, and the soils, where present, are thin and rocky.

Erosion has produced extensive lines of prominent cliffs in the region. The tops of these cliffs are generally underlain and protected by resistant sandstones. Erosion of the domes has produced a series of concentric, steeply dipping ridges, also developed on the more resistant sandstones.

Recharge of the sandstone aquifers occurs where they are exposed above the cliffs and in the ridges.

Average precipitation ranges from about 150 mm in the lower areas to about 1,000 mm in the higher mountains. The heaviest rainfall occurs in the summer in isolated, intense thunderstorms during which some recharge occurs where intermittent streams flow across sandstone outcrops. However, most recharge occurs in the winter during snowmelt periods. Water moves down the dip of the beds away from the recharge areas to discharge along the channels of major streams through seeps and springs and along the walls of canyons cut by the streams.

The condition described in the preceding paragraph, whereby intermittent streams serve as sources of ground-water recharge and perennial streams serve as lines of ground-water discharge, is relatively common in this region and in the Alluvial Basins region to the south and west. Streams into which ground water discharges are referred to as gaining streams. Conversely, streams that recharge ground-water systems are referred to as losing streams. The gaining streams and the losing streams may be different streams. However, in many areas the same stream may be a gaining stream in its headwaters, especially where these drain the wetter mountainous areas, become a losing stream as it flows onto the adjoining lower areas, and, ultimately, become a gaining stream again in its lowermost reaches where it serves as a regional drain.

The quantity of water available for recharge is small, but so are the porosity and the transmissivity of most of the sandstone aquifers. Because of the general absence of a thick cover of unconsolidated rock in the recharge areas, there is relatively little opportunity for such materials to serve as a storage reservoir for the underlying bedrock. The water in the sandstone aquifers is unconfined in the recharge areas and is confined down-dip. Because most of the sandstones are consolidated, the storage coefficient in the confined parts of the aquifers is very small. This small storage coefficient together with the small transmissivities, results in even smaller rates of withdrawal causing extensive cones of depression around pumping wells.

Springs exist at places near the base of the sandstone aquifers where they crop out along the sides of canyons. Discharge from the springs results in dewatering the upper parts of the aquifers for some distance back from the canyon walls.

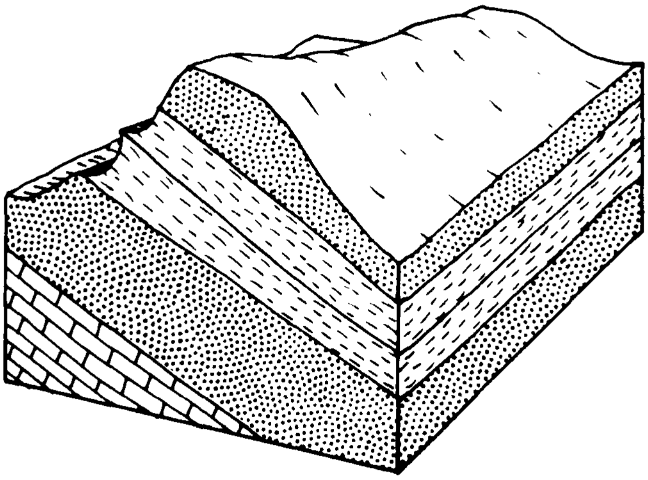
The Colorado Plateau and Wyoming Basin is a dry, sparsely populated region in which most water supplies are obtained from the perennial streams that flow across it from the bordering mountains. Less than 5 percent of the water needs are supplied by ground water, and the development of even small ground-water supplies requires the application of considerable knowledge of the occurrence of both rock units and their structure, and of the chemical quality of the water. Also, because of the large surface relief and the dip of the aquifers, wells even for domestic or small livestock supplies must penetrate to depths of a few hundred meters in much of the area. Thus, the development of ground-water supplies is far more expensive than in most other parts of the country. These negative aspects notwithstanding, ground water in the region can support a substantial increase over the present withdrawals.

As in most other areas of the country underlain by consolidated sedimentary rocks, mineralized (saline) water—that is, water containing more than 1,000 mg/l of dissolved solids—is widespread in occurrence. Most of the shales and siltstones contain mineralized water throughout the region and below altitudes of about 2,000 m. Freshwater—water containing less than 1,000 mg/l of dissolved solids—occurs only in the most permeable sandstones and limestones. Much of the mineralized water is due to the solution of gypsum and halite by water circulating through beds that contain these minerals. Although the aquifers that contain mineralized water are commonly overlain by aquifers containing freshwater, this situation is reversed in a few places where aquifers containing mineralized water are underlain by more permeable aquifers containing freshwater.

Colorado Plateau and Wyoming Basin

(4A) Resistant Ridges

This hydrogeologic setting is characterized by moderate to steep slopes, and a very thin soil cover which overlies dipping fractured consolidated sedimentary rocks. The resistant sandstones cap the cliffs and ridges and form hogbacks. These same sandstone units comprise the aquifers that are the principal sources of ground water. The aquifers receive recharge in the areas where the sandstone is exposed at the surface. Recharge is low because of the topography and the lack of precipitation in the area. Water levels are extremely variable, but are typically deep.



Setting 4 A Resistant Ridges

Feature	Range	General Weight	General Rating	General Number
Depth to Water Table	75-100	5	2	10
Net Recharge	0-2	4	1	4
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Thin or Absent	2	10	20
Topography	12-18%	1	3	3
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	1-100	3	1	3
		DRASTIC Index		88

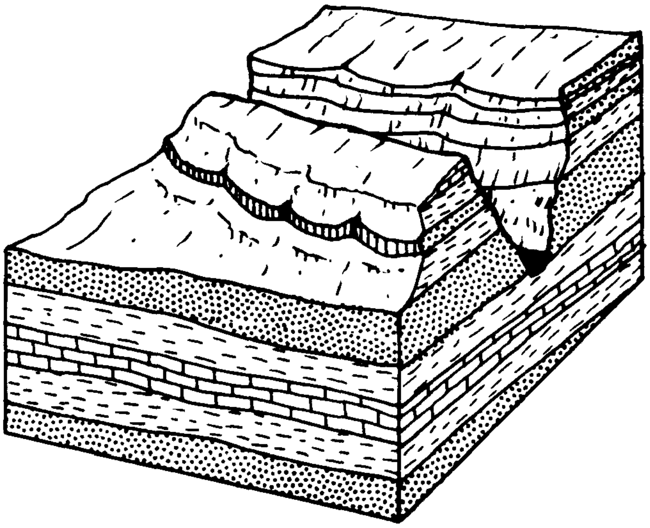
Setting 4 A Resistant Ridges

Feature	Range	Agricultural Weight	Agricultural Rating	Agricultural Number
Depth to Water Table	75-100	5	2	10
Net Recharge	0-2	4	1	4
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Thin or Absent	5	10	50
Topography	12-18%	3	3	9
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	1-100	2	1	2
		Agricultural DRASTIC Index		117

Colorado Plateau and Wyoming Basin

(4B) Consolidated Sedimentary Rocks

This hydrogeologic setting is characterized by alternating layers of moderately-dipping, fractured, consolidated, sedimentary rocks covered by a sandy soil layer which commonly weathers to a sandy loam. The sandstones serve as the principal source of ground water. The water is obtained from fractures developed along bedding planes and from within the pore spaces. Water levels are typically deep and recharge is low because of the lack of precipitation. Intermittent streams often serve as sources of recharge, however, the major source of recharge occurs in the resistant ridges where the bedrock is exposed. The sandstones may be also confined, with small storage values and low yield wells.



Setting 4 B Consolidated Sedimentary Rocks

Feature	Range	General Weight	General Rating	General Number
Depth to Water Table	50-75	5	3	15
Net Recharge	0-2	4	1	4
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	2	6	12
Topography	6-12%	1	5	5
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	1-100	3	1	3
		DRASTIC Index		87

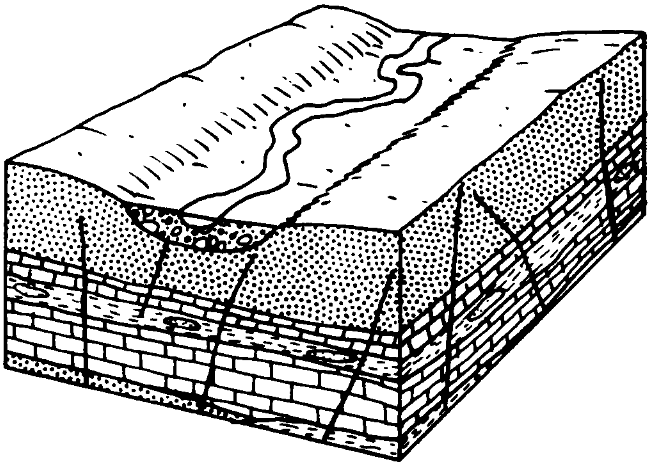
Setting 4 B Consolidated Sedimentary Rocks

Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	50-75	5	3	15
Net Recharge	0-2	4	1	4
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	5	6	30
Topography	6-12%	3	5	15
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	1-100	2	1	2
		Agricultural DRASTIC Index		108

Colorado Plateau and Wyoming Basin

(4C) River Alluvium

This hydrogeologic setting is characterized by low topography and deposits of alluvium along parts of valleys of perennial and intermittent streams. The alluvium yields small to moderate supplies of ground water. Water is obtained from sand and gravel layers which are interbedded with finer-grained alluvial deposits; these are usually in direct hydraulic contact with the perennial or intermittent stream. Water levels are extremely variable but are commonly moderately shallow. Although precipitation is low, recharge is significant due to the low topography and sandy loam soil cover. The alluvium is underlain by consolidated sedimentary rocks which are often in direct hydraulic connection with the overlying deposits.



Setting 4 C River Alluvium

Feature	Range	General Weight	Rating	Number
Depth to Water Table	15-30	5	9	45
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	S & G w/sig Silt and Clay	5	6	30
Hydraulic Conductivity	700-1000	3	6	18
		DRASTIC Index		162

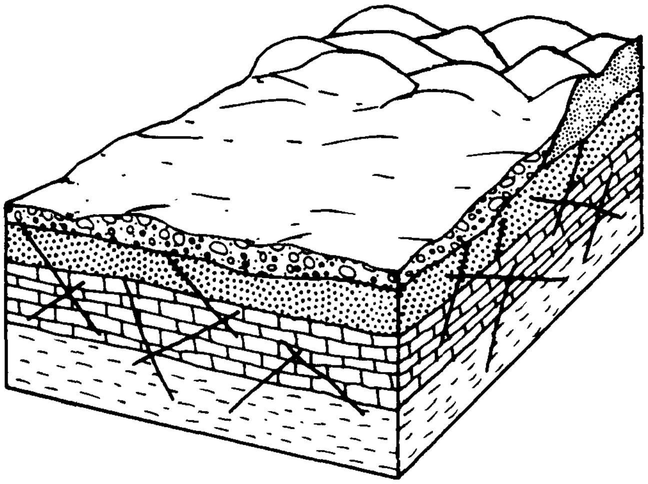
Setting 4 C River Alluvium

Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	15-30	5	9	45
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	S & G w/sig Silt and Clay	4	6	24
Hydraulic Conductivity	700-1000	2	6	12
		Agricultural DRASTIC Index		186

Colorado Plateau and Wyoming Basin

(4D) Alluvium and Dune Sand

This hydrogeologic setting is characterized by moderate topography derived from unconsolidated alluvial sediments that have formed under various depositional environments. These alluvial deposits vary from lacustrine deposits in the Wyoming Basin area to dune sands in the Navajo area of northern Arizona and northwestern New Mexico. Much of the entire region is covered by thin alluvium. The hydraulic conductivity of the alluvium is high throughout the area, including the sand dunes portion. Recharge is limited by low precipitation and evaporation. The alluvium serves as moderate water supplies in some areas; provides some discharge to streams, and acts as storage for recharge to deeper aquifers.



Setting 4 D Alluvium and Dune Sand

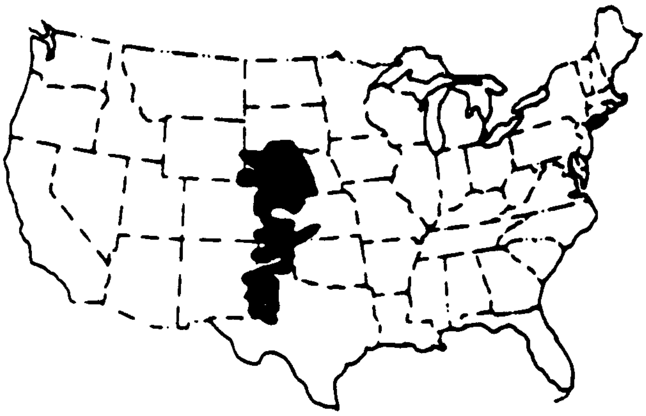
Feature	Range	General Weight	Rating	Number
Depth to Water Table	50-75	5	3	15
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	6-12%	1	5	5
Impact Vadose Zone	S & G w/sig. Silt and Clay	5	6	30
Hydraulic Conductivity	100-300	3	2	6
		DRASTIC Index		102

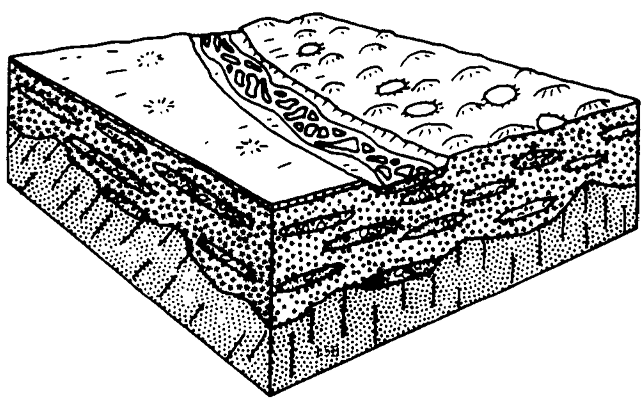
Setting 4 D Alluvium and Dune Sand

Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	50-75	5	3	15
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	6-12%	3	5	15
Impact Vadose Zone	S & G w/sig. Silt and Clay	4	6	24
Hydraulic Conductivity	100-300	2	2	4
		Agricultural DRASTIC Index		131

5. *High Plains*

(Thick alluvial deposits over fractured sedimentary rocks)





The High Plains region occupies an area of 450,000 km^2 extending from South Dakota to Texas. The plains are a remnant of a great alluvial plain built in Miocene time by streams that flowed east from the Rocky Mountains. The plain originally extended from the foot of the mountains to a terminous some hundreds of kilometers east of its present edge. Erosion by streams has removed a large part of the once extensive plain, including all of the part adjacent to the mountains, except in a small area in southeastern Wyoming.

The original depositional surface of the alluvial plain is still almost unmodified in large areas, especially in Texas and New Mexico, and forms a flat, imperceptibly eastward-sloping tableland that ranges in altitude from about 2,000 m near the Rocky Mountains to about 500 m along its eastern edge. The surface of the southern High Plains contains numerous shallow circular depressions, called playas, that intermittently contain water following heavy rains. Some geologists believe these depressions are due to solution of soluble materials by percolating water and accompanying compaction of the alluvium. Other significant topographic features include sand dunes, which are especially prevalent in central and northern Nebraska, and wide, downcut valleys of streams that flow eastward across the area from the Rocky Mountains.

The High Plains region is underlain by one of the most productive and most intensively developed aquifers in the United States. The alluvial materials derived from the Rocky Mountains, which are referred to as the Ogallala Formation, are the dominant geologic unit of the High Plains aquifer. The Ogallala ranges in thickness from a few meters to more than 200 m and consists of poorly sorted and generally unconsolidated clay, silt, sand, and gravel.

Younger alluvial materials of Quaternary age overlie the Ogallala Formation of late Tertiary age in most parts of the High Plains. Where these deposits are saturated, they form a part of the High Plains aquifer; in parts of south-central Nebraska and central Kansas, where the Ogallala is absent, they comprise the entire aquifer. The Quaternary deposits are composed largely of material derived from the Ogallala and consist of alluvial deposits of gravel, sand, silt, and clay and extensive areas of sand dunes. The most extensive area of dune sand occurs in the Sand Hills area north of the Platte River in Nebraska.

Other, older geologic units that are hydrologically connected to the Ogallala thus form a part of the High Plains aquifer, include the Arikaree Group of Miocene age and a small part of the underlying Brule Formation. The Arikaree Group underlies the Ogallala in parts of western Nebraska, southwestern South Dakota, southeastern Wyoming, and northeastern

Colorado. It is predominantly a massive, very fine to fine-grained sandstone that locally contains beds of volcanic ash, silty sand, and sandy clay. The maximum thickness of the Arikaree is about 300 m, in western Nebraska. The Brule Formation of Oligocene age underlies the Arikaree. In most of the area in which it occurs, the Brule forms the base of the High Plains aquifer. However, in the southeastern corner of Wyoming and the adjacent parts of Colorado and Nebraska, the Brule contains fractured sandstones hydraulically interconnected to the overlying Arikaree Group; in this area the Brule is considered to be a part of the High Plains aquifer.

In the remainder of the region, the High Plains aquifer is underlain by several formations, ranging in age from Cretaceous to Permian and composed principally of shale, limestone, and sandstone. The oldest of these, of Permian age, underlies parts of northeastern Texas, western Oklahoma, and central Kansas and contains layers of relatively soluble minerals including gypsum, anhydrite, and halite (common salt) which are dissolved by circulating ground water. Thus, water from the rocks of Permian age is relatively highly mineralized and not usable for irrigation and other purposes that require freshwater. The older formations in the remainder of the area contain fractured sandstones and limestones interconnected in parts of the area with the High Plains aquifer. Although these formations yield freshwater, they are not widely used as water sources.

Prior to the erosion that removed most of the western part of the Ogallala, the High Plains aquifer was recharged by the streams that flowed onto the plain from the mountains to the west as well as by local precipitation. The only source of recharge now is local precipitation, which ranges from about 400 mm along the western boundary of the region to about 600 mm along the eastern boundary. Precipitation and ground-water recharge on the High Plains vary in an east-west direction, but recharge to the High Plains also varies in a north-south direction. The average annual rate of recharge has been determined to range from about 5 mm in Texas and New Mexico to about 100 mm in the Sand Hills in Nebraska. This large difference is explained by differences in evaporation and transpiration and by differences in the permeability of the surficial materials.

In some parts of the High Plains, especially in the southern part, the near-surface layers of the Ogallala have been cemented with lime (calcium carbonate) to form a material of relatively low permeability called caliche. Precipitation on areas underlain by caliche soaks slowly into the ground. Much of this precipitation collects in playas that are underlain by silt and clay, which hamper infiltration, with the result that most of the water is lost to evaporation. During years of average or below average precipitation, all or nearly all of the precipitation is returned to the atmosphere by evapotranspiration. Thus, it is only during years of excessive precipitation that significant recharge occurs and this, as noted above, averages only about 5 mm per year in the southern part of the High Plains.

In the Sand Hills area, the lower evaporation and transpiration and the permeable sandy soil results in about 20 percent of the precipitation (or about 100 mm annually) reaching the water table as recharge.

The water table of the High Plains aquifer has a general slope toward the east of about 2 to 3 m per km (10 to 15 ft per mile). Gutentag and Weeks (1980) estimate, on the basis of the average hydraulic gradient and aquifer characteristics, that water moves through the aquifer at a rate of about 0.3 m (1 ft) per day.

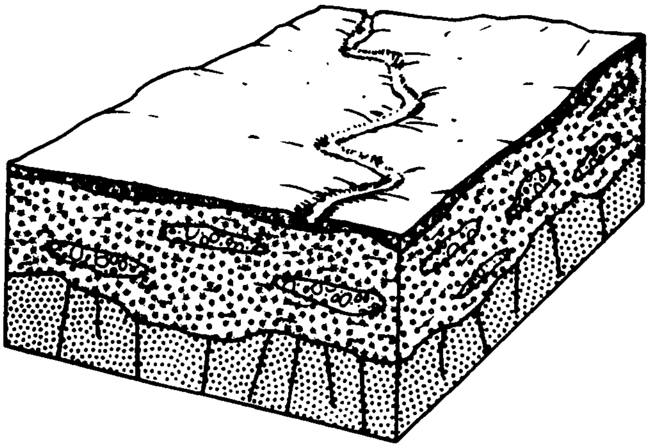
Natural discharge from the aquifer occurs to streams, to springs and seeps along the eastern boundary of the plains, and by evaporation and transpiration in areas where the water table is within a few meters of the land surface. However, at present the largest discharge is probably through wells. The widespread occurrence of permeable layers of sand and gravel, which permit the construction of large-yield wells almost any place in the region, has led to the development of an extensive agricultural economy largely dependent on irrigation. Gutentag and Weeks (1980) estimate that in 1977 about 3.7 x 10^{10} m^3 (30,000,000 acre-ft) of water was pumped from more than 168,000 wells to irrigate about 65,600 km^2 (16,210,000 acres). Most of this water is derived from ground-water storage, resulting in a long-term continuing decline in ground-water levels in parts of the region of as much as 1 m per year. The lowering of the water table has resulted in a 10 to 50 percent reduction in the saturated thickness of the High Plains aquifer in an area of 130,000 km^2 (12,000 mi^2). The largest reductions have occurred in the Texas panhandle and in parts of Kansas and New Mexico.

The depletion of ground-water storage in the High Plains, as reflected in the decline in the water table and the reduction in the saturated thickness, is a matter of increasing concern in the region. However, from the standpoint of the region as a whole, the depletion does not yet represent a large part of the storage that is available for use. Weeks and Gutentag (1981) estimate, on the basis of a specific yield of 15 percent of the total volume of saturated material, that the available (usable) storage in 1980 was about 4 x 10^{12} m^3 (3.3 billion acre-ft). Luckey, Gutentag, and Weeks (1981) estimate that this is only about 5 percent less than the storage that was available at the start of withdrawals. However, in areas where intense irrigation has long been practiced, depletion of storage is severe.

High Plains

(5A) Ogallala

This hydrogeologic setting is characterized by moderately flat topography and thick deposits of poorly-sorted, semi-consolidated, clay, silt, sand and gravel that may be underlain by fractured sedimentary rock which are in hydraulic connection with overlying deposits. In some parts of the High Plains, especially in the southern part, shallow zones of the unconsolidated deposits have been cemented with calcium carbonate. The permeability of this caliche layer varies with the degree of cementation, fracturing, and clay mineral content. Precipitation averages less than 20 inches per year and recharge is very low throughout most of this water deficient area. The bedrock and the overlying semi-consolidated deposits both serve as extensive sources of ground water. Water levels are typically deep, but extremely variable. The Ogallala is underlain by bedded, unconsolidated deposits of fractured sandstone, volcanic ash, silty sand, sandy clay, and shales. These formations are hydraulically connected to the Ogallala, and the overlying alluvium, from which they derive their recharge.



Setting 5 A Ogallala

Feature	Range	General Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Shrink/Agg. Clay	2	7	14
Topography	2-6%	1	9	9
Impact Vadose Zone	S & G w/sig. Silt and Clay	5	6	30
Hydraulic Conductivity	700-1000	3	6	18

DRASTIC Index 109

Setting 5 A Ogallala

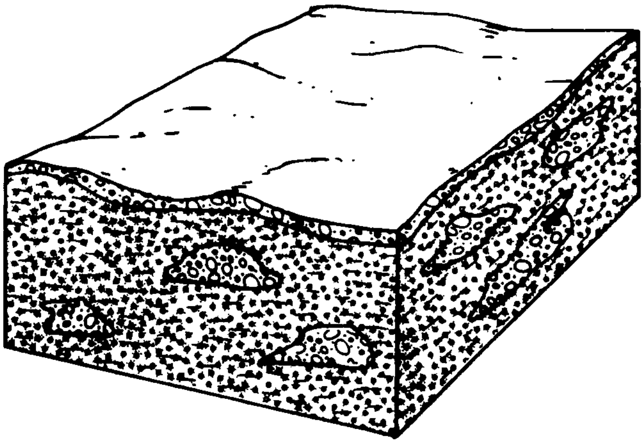
Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Shrink/Agg. Clay	5	7	35
Topography	2-6%	3	9	27
Impact Vadose Zone	S & G w/sig. Silt and Clay	4	6	24
Hydraulic Conductivity	700-1000	2	6	12

Agricultural DRASTIC Index 136

High Plains

(5B) Alluvium

This hydrogeologic setting is characterized by low to moderate relief, and is comprised of gravel, sand, silt, and clay alluvial sediments. These deposits are variable in thickness. They form, where saturated, a portion of the High Plains aquifer, and locally all of it where the Ogallala is missing. Water levels are variable, but typically deep. Recharge is limited throughout most of the area by low precipitation. The shallow caliche layer of cemented, unconsolidated deposits also develops in the alluvium in some localities. Similar to the Ogallala, recharge to the deeper sandstones is through the alluvial deposits.



Setting 5 B Alluvium

Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	50-75	5	3	15
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	0-2%	1	10	10
Impact Vadose Zone	S & G w/sig. Silt and Clay	5	6	30
Hydraulic Conductivity	300-700	3	4	12

DRASTIC Index 107

Setting 5 B Alluvium

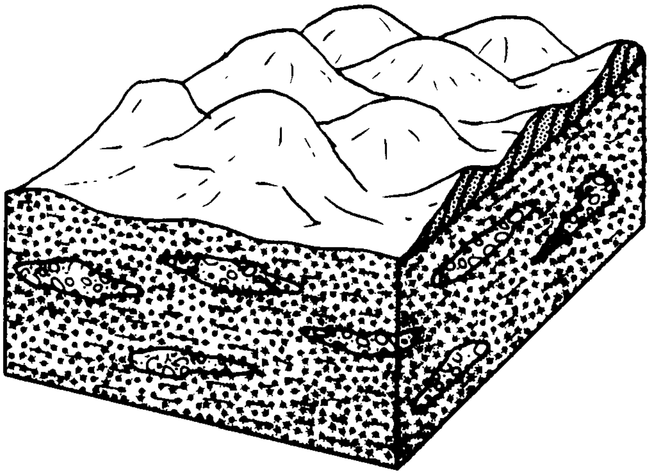
Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	50-75	5	3	15
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	0-2%	3	10	30
Impact Vadose Zone	S & G w/sig. Silt and Clay	4	6	24
Hydraulic Conductivity	300-700	2	4	8

Agricultural DRASTIC Index 135

High Plains

(5C) Sand Dunes

This hydrogeologic setting is characterized by hilly topography comprised of sand dunes which overlie thick poorly-sorted sand and gravel deposits. The sand dunes are in direct hydraulic connection with the underlying deposits. Because of their relatively low water table, these dunes do not serve as sources of ground water, but serve as local recharge areas. In contrast to other areas of the High Plains, recharge rates are higher due to lower evaporation and permeable sandy soils, but are limited by available precipitation.



Setting 5 C Sand Dunes

Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	30-50	5	5	25
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	2000+	3	10	30

DRASTIC Index 150

Setting 5 C Sand Dunes

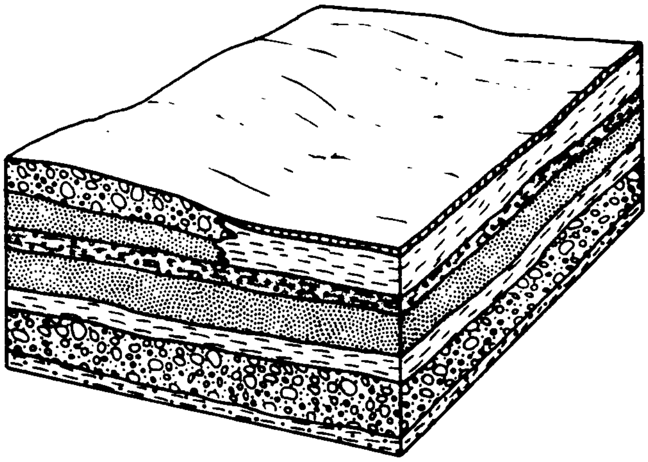
Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	30-50	5	5	25
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	2000+	2	10	20

Agricultural DRASTIC Index 177

High Plains

(5D) Playa Lakes

This hydrogeologic setting is characterized by low topographic relief and thin layers of clays and other fine grained sediments which overlie the alluvial deposits. The playa areas serve as a catchment for water during periods of significant runoff. Ground water is obtained from the layers of sand which underlie the finer-grained deposits. Water levels are extremely variable, but are typically deep. The playa beds are significant recharge areas due to the rainfall that collects in them. The rate of recharge, as compared to evaporation, is largely a function of the permeability of the materials forming the bed of the playa, and the distribution, in time, of precipitation.



Setting 5 D Playa Lakes

Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	75-100	5	2	10
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Shrink/Agg. Clay	2	7	14
Topography	0-2%	1	10	10
Impact Vadose Zone	S & G w/sig Silt and Clay	5	6	30
Hydraulic Conductivity	700-1000	3	6	18

DRASTIC Index 110

Setting 5 D Playa Lakes

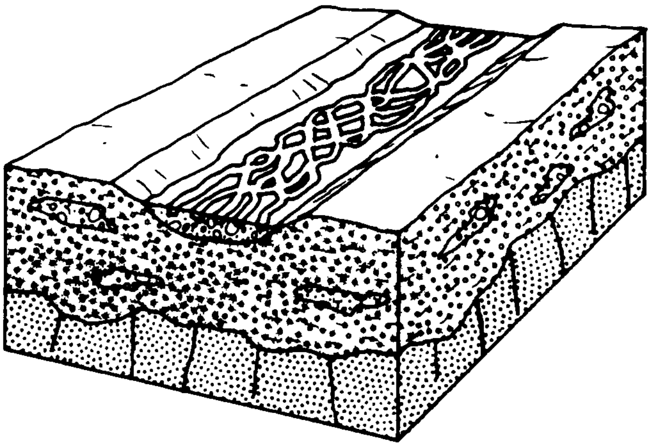
Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	75-100	5	2	10
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Shrink/Agg. Clay	5	7	35
Topography	0-2%	3	10	30
Impact Vadose Zone	S & G w/sig. Silt and Clay	4	6	24
Hydraulic Conductivity	700-1000	2	6	12

Agricultural
DRASTIC Index 139

High Plains

(5E) Braided River Deposits

This hydrogeologic setting is characterized by deposits of alluvium which occur within the flood plain of streams and rivers. The stream is characterized by a low gradient, wide channel and a series of interconnected shallow channels which form a braided pattern. Water levels are typically shallow, and some streams may be intermittent. The river alluvium sometimes serves as a significant source of ground water but is most important as a source of recharge since it overlies more productive semi-consolidated deposits. The underlying deposits are in direct hydraulic connection with the overlying alluvium, so the potential for pollution of the aquifer is high. Although precipitation, which averages less than 20 inches per year is a limiting factor, recharge may be very high due to seasonal or perennial stream flow on these very permeable deposits.



Setting 5 E Braided River Deposits

Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	5-15	5	9	45
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	0-2%	1	10	10
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	1000-2000	3	8	24

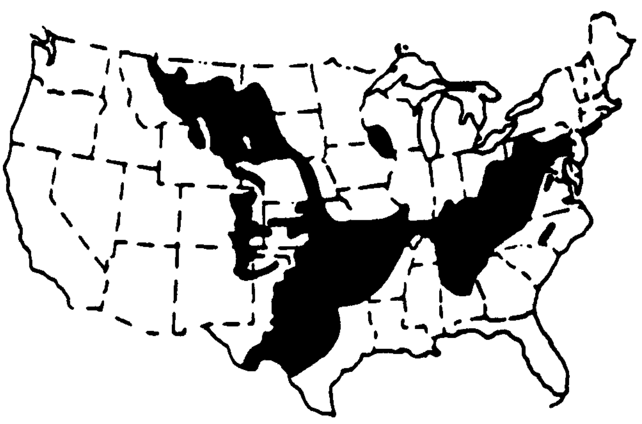
DRASTIC Index 185

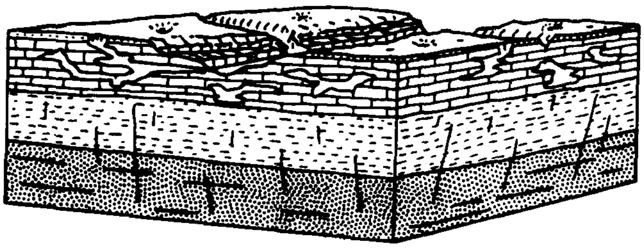
Setting 5 E Braided River Deposits

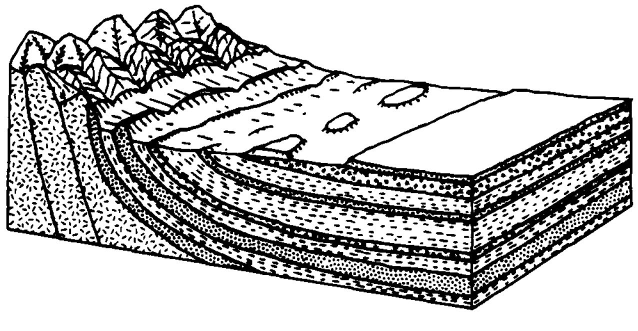
Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	0-2%	3	10	30
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	1000-2000	2	8	16
		Agricultural DRASTIC Index		216

6. *Nonglaciated Central Region*

(Thin regolith over fractured sedimentary rocks)







The nonglaciated Central region is an area of about 1,737,000 km^2 extending from the Appalachian Mountains on the east to the Rocky Mountains on the west. The part of the region in eastern Colorado and northeastern New Mexico is separated from the remainder of the region by the High Plains region. The Nonglaciated Central region also includes the Triassic Basins in Virginia and North Carolina and the "driftless" area in Wisconsin, Minnesota, Iowa, and Illinois where glacial deposits, if present, are thin and of no hydrologic importance. The region is a topographically complex area that ranges from the Valley and Ridge section of the Appalachian Mountains on the east westward across the Great Plains to the foot of the Rocky Mountains. It includes, among other hilly and mountainous areas, the Ozark Plateaus in Missouri and Arkansas. Altitudes range from 150 m above sea level in central Tennessee and Kentucky to 1,500 m along the western boundary of the region.

The region is also geologically complex. Most of it is underlain by consolidated sedimentary rocks that range in age from Paleozoic to Tertiary and consist largely of sandstone, shale, carbonate rocks (limestone and dolomite), and conglomerate. A small area in Texas and western Oklahoma is underlain by gypsum. Throughout most of the region the rock layers are horizontal or gently dipping. Principal exceptions are the Valley and Ridge section of the Wichita and Arbuckle Mountains in Oklahoma, and the Ouachita Mountains in Oklahoma and Arkansas, in all of which the rocks have been folded and extensively faulted. Around the Black Hills and along the eastern side of the Rocky Mountains the rock layers have been bent up sharply toward the mountains and truncated by erosion. The Triassic Basins in Virginia and North Carolina are underlain by moderate- to gently dipping beds of shale and sandstone that have been extensively faulted and invaded by narrow bodies of igneous rock. These basins were formed in Triassic time when major faults in the crystalline rocks of the Piedmont resulted in the formation of structural depressions up to several thousand meters deep and more than 25 km wide and 140 km long.

The land surface in most of the region is underlain by regolith formed by chemical and mechanical breakdown of the bedrock. In the western part of the Great

Plains the residual soils are overlain by or intermixed with eolian (wind-laid) deposits. The thickness and composition of the regolith depend on the composition and structure of the parent rock and on the climate, land cover, and topography. In areas underlain by relatively pure limestone, the regolith consists mostly of clay and is generally only a few meters thick. Where the limestones contain chert and in areas underlain by shale and sandstone, the regolith is thicker, up to 30 m or more in some areas. The chert and sand form moderately permeable soils, whereas the soils developed on shale are finer grained and less permeable.

The principal water-bearing openings in the bedrock are fractures along which the rocks have been broken by stresses imposed on the Earth's crust at different times since the rocks were consolidated. The fractures generally occur in three sets. The first set, and the one that is probably of greatest importance from the standpoint of ground water and well yields, consists of fractures developed along the contact between different rock layers, in other words, along bedding planes. Where the sedimentary layers making up the bedrock are essentially horizontal, the bedding-plane fractures are more or less parallel to the land surface. The two remaining sets of fractures are essentially vertical and thus cross the bedding planes at a steep angle. The primary difference between the sets of vertical fractures is in the orientation of the fractures in each set. For example, in parts of the region one set of vertical fractures is oriented in a northwest-southeast direction and the other set in a northeast-southwest direction. The vertical fractures facilitate movement of water across the rock layers and thus serve as the principal hydraulic connection between the bedding-plane fractures.

In parts of the region in which the bedrock has been folded or bent, the occurrence and orientation of fractures are more complex. In these areas the dip of the rock layers and the associated bedding-plane fractures range from horizontal to vertical. Fractures parallel to the land surface, where present, are probably less numerous and of more limited extent than in areas of flat-lying rocks.

The openings developed along most fractures are less than a millimeter wide. The principal exception occurs in limestones and dolomites, which are more soluble in water than most other rocks. Water moving through these rocks gradually enlarges the fractures to form, in time, extensive cavernous openings or cave systems. Many large springs emerge from these openings; one in this region is Big Spring, in Missouri, which has an average discharge of 36.8 $m^3 sec^{-1}$.

Recharge of the ground-water system in this region occurs primarily in the outcrop areas of the bedrock aquifers in the uplands between streams. Precipitation in the region ranges from about 400 mm per year in the western part to more than 1,200 mm in the eastern part. This wide difference in precipitation is reflected in recharge rates, which range from about 5 mm per year in west Texas and New Mexico to as much as 500 mm per year in Pennsylvania and eastern Tennessee. Discharge from the ground-water system is by springs and seepage into streams and by evaporation and transpiration in areas where the water table is within a few meters of land surface.

The yield of wells depends on (1) the number and size of fractures that are penetrated and the extent to which they have been enlarged by solution, (2) the rate of recharge, and (3) the storage capacity of the bedrock and regolith. Yields of wells in most of the region are small, in the range of 0.01 to 1 $m^3 min^{-1}$ (about 2.5 to about 250 gallons per minute), making the Nonglaciated Central region one of the least favorable ground-water regions in the country. Even in parts of the areas underlain by cavernous limestone, yields are moderately low because of both the absence of a thick regolith and the large water-transmitting capacity of the cavernous openings which quickly discharge the water that reaches them during periods of recharge.

The exceptions to the small well yields are the cavernous limestones of the Edwards Plateau, the Ozark Plateaus, and the Ridge and Valley section. The Edwards Plateau in Texas is bounded on the south by the Balcones Fault Zone, in which limestone and dolomite up to 150 m in thickness has been extensively faulted. The faulting has facilitated the development of solution openings which makes this zone one of the most productive aquifers in the country. Wells of the City of San Antonio are located in this zone; individually, they have yields of more than 60 $m^3 min^{-1}$.

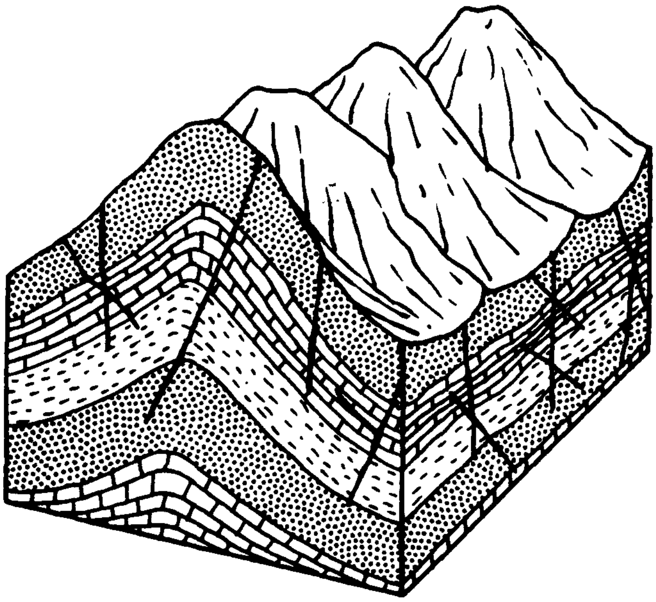
Another feature that makes much of this region unfavorable for ground-water development is the occurrence of salty water at relatively shallow depths. In most of the Nonglaciated Central region, except the Ozark Plateaus, the Ouachita and Arbuckle Mountains, and the Ridge and Valley section, the water in the bedrock contains more than 1,000 mg/l of dissolved solids at depths less than 150 m. Most of the salty water is believed to be connate—that is, it was trapped in the rocks when they emerged from the sea in which they were deposited. Other possible sources include: (1) seawater that entered the rocks during a later time when the land again was beneath the sea; and (2) salty water derived from solution of salt beds that underlie parts of the region.

The presence of connate water at relatively shallow depths is doubtless due to several factors, including, in the western part of the area, a semiarid climate and, consequently, a small rate of recharge. Other factors probably include an extremely slow rate of ground-water circulation at depths greater than a few hundred meters.

Non-Glaciated Central

(6A) Mountain Slopes

This hydrogeologic setting is characterized by relatively steep slopes on the side of mountains or hills, a thin soil cover and fractured bedrock. Ground water is obtained primarily from the fractures in the bedrock which may be of sedimentary, metamorphic or igneous origin but which are commonly alternating sedimentary layers, and also from bedding planes between the sedimentary layers. The fractures provide only localized sources of ground water and well yields are typically limited. Although precipitation may be significant in some areas, due to the steep slopes, thin soil cover, and small storage capacity of the fractures, runoff is significant and ground-water recharge is low. Water levels are extremely variable but are commonly moderately deep. Perched ground-water zones are common. These sedimentary rocks may range in attitude from nearly horizontal, as in parts of the western Appalachian Plateau, to steeply dipping, as seen in the Valley and Ridge province, the Wichita, Arbuckle, and Ouachita Mountains, the Black Hills, and on the eastern slopes of the Rockies.



Setting 6 A Mountain Slopes

Feature	Range	General Weight	General Rating	General Number
Depth to Water Table	30-50	5	5	25
Net Recharge	0-2	4	1	4
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Thin or Absent	2	10	20
Topography	12-18%	1	3	3
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	1-100	3	1	3

DRASTIC Index 103

Setting 6 A Mountain Slopes

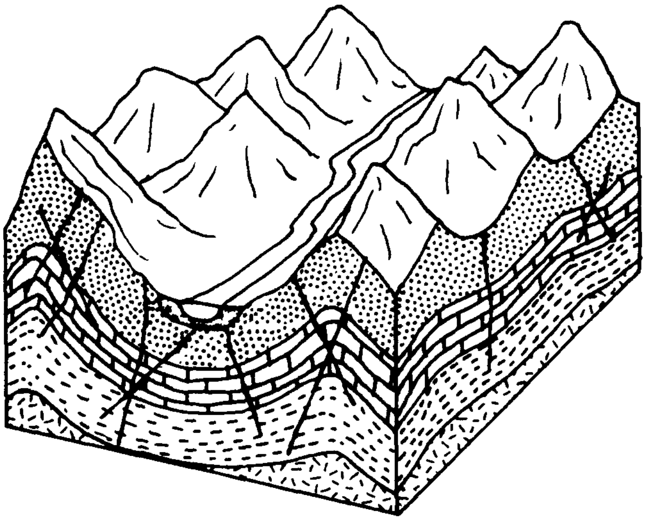
Feature	Range	Agricultural Weight	Agricultural Rating	Agricultural Number
Depth to Water Table	30-50	5	5	25
Net Recharge	0-2	4	1	4
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Thin or Absent	5	10	50
Topography	12-18%	3	3	9
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	1-100	2	1	2

Agricultural DRASTIC Index 132

Non-Glaciated Central

(6B) Alluvial Mountain Valleys

This hydrogeologic setting is characterized by thin bouldery alluvium which overlies fractured bedrock of sedimentary, metamorphic or igneous origin but which is commonly comprised of alternating sedimentary layers. The alluvium, which is derived from the surrounding slopes, serves as a localized source of water. Water is obtained from sand and gravel layers which are interspersed between finer-grained deposits. Surficial deposits have typically weathered to a sandy loam. Water levels are relatively shallow but may be extremely variable. Ground water may also be obtained from the fractures in the underlying bedrock which are typically in direct hydraulic connection with the overlying alluvium.



Non-Glaciated Central

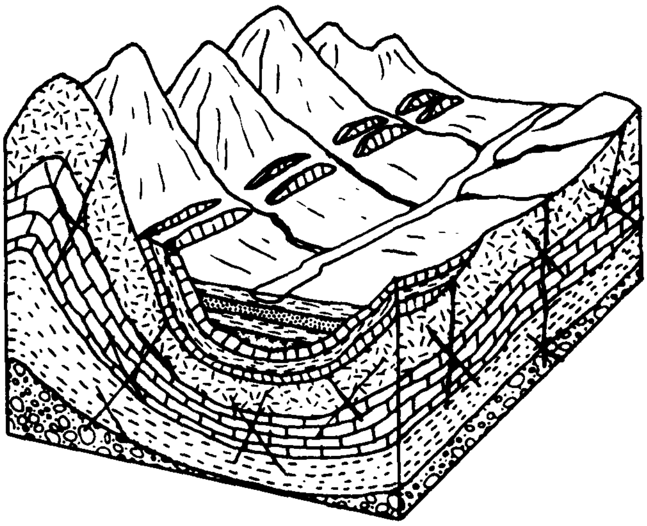
(6C) Mountain Flanks

This hydrogeologic setting is characterized by moderate topographic relief and moderately-dipping, fractured, consolidated, sedimentary rocks. Soil cover is usually thicker than on the mountain slopes and typically has weathered to a sandy loam. Although precipitation can be significant, ground-water recharge is only moderate due to the slope. Water levels are typically moderately deep although they are extremely variable. The mountain flanks serve as the recharge area for aquifers which are confined in adjacent areas. Ground water is obtained from the permeable sedimentary rocks or from fractures in the sedimentary rocks. The sedimentary rocks may be underlain by fractured bedrock of igneous, metamorphic or sedimentary origin which yield little water. Sedimentary beds may be either horizontal or dipping, as indicated for the higher mountain slopes (6A), and have a similar geographic distribution.

Setting 6 B Alluvial Mountain Valleys

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	S & G w/sig. Silt and Clay	5	6	30
Hydraulic Conductivity	700-1000	3	6	18

DRASTIC Index 152



Setting 6 B Alluvial Mountain Valleys

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	S & G w/sig. Silt and Clay	4	6	24
Hydraulic Conductivity	700-1000	2	6	12

Agricultural
DRASTIC Index 176

Setting 6 C Mountain Flanks

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	2-4	4	3	12
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	2	6	12
Topography	6-12%	1	5	5
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	1-100	3	1	3

DRASTIC Index 105

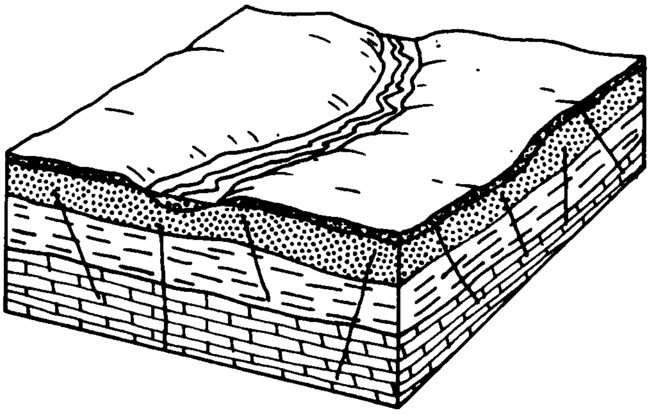
Setting 6 C Mountain Flanks

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	2-4	4	3	12
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	5	6	30
Topography	6-12%	3	5	15
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	1-100	2	1	2
		Agricultural DRASTIC Index		126

Non-Glaciated Central

(6Da) Alternating SS, LS, and SH—Thin Soil

This hydrogeologic setting is characterized by low to moderate topographic relief, relatively thin loamy soils overlying horizontal or slightly dipping alternating layers of fractured consolidated sedimentary rocks. Ground water is obtained primarily from fractures along bedding planes or intersecting vertical fractures. Precipitation varies widely in the region, but recharge is moderate where precipitation is adequate. Water levels are extremely variable but on the average moderately shallow. Shale or clayey layers often form aquitards, and where sufficient relief is present, perched ground-water zones of local domestic importance are often developed.



Setting 6 Da Alternating SS, LS, SH—Thin Soil

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Loam	2	5	10
Topography	2-6%	1	9	9
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	1-100	3	1	3
		DRASTIC Index		129

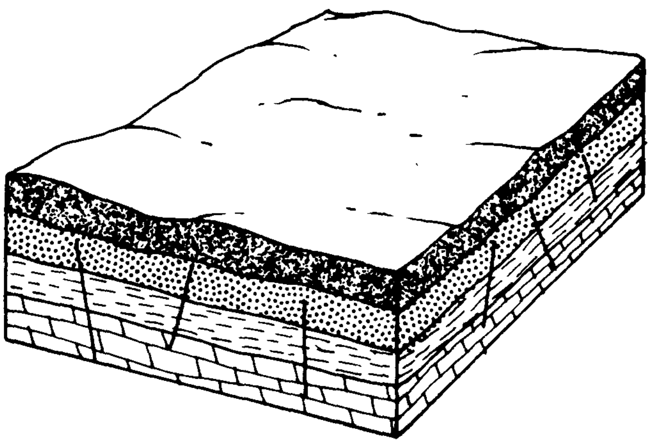
Setting 6 Da Alternating SS, LS, SH—Thin Soil

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Loam	5	5	25
Topography	2-6%	3	9	27
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	1-100	2	1	2
		Agricultural DRASTIC Index		155

Non-Glaciated Central

(6Db) Alternating SS, LS, and SH—Deep Regolith

This hydrogeologic setting is identical to 6Da Alternating SS, LS, and SH—Thin Soil except that the surficial deposits typically have been weathered to form clay loams which grade into weathered bedrock which help retard the movement of pollutants through the ground to the water table. These thick soil deposits are usually in direct, hydraulic connection with the underlying fractured sedimentary deposits.



Setting 6 Db Alternating SS, LS, SH—Deep Regolith

Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	1-100	3	1	3

DRASTIC Index 131

Setting 6 Db Alternating SS, LS, SH—Deep Regolith

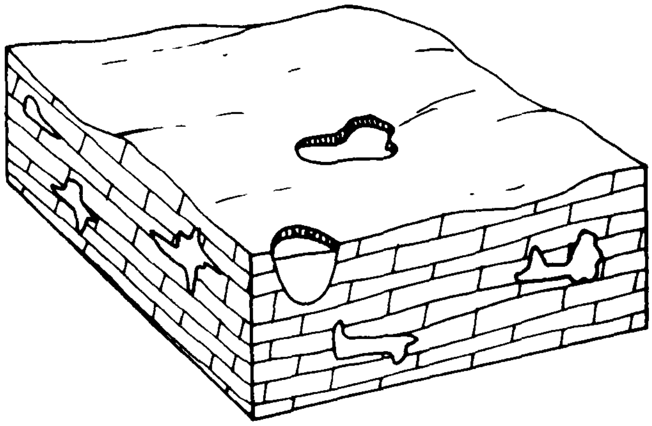
Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	1-100	2	1	2

Agricultural DRASTIC Index 160

Non-Glaciated Central

(6E) Solution Limestone

This hydrogeologic setting is characterized by moderate, but variable, topographic relief and deposits of limestone which have been partially dissolved along bedding and fracture planes to form a network of solution cavities and caves. Soil is usually thin or absent, but where present is commonly a clayey loam. Recharge is usually greater than 10 inches per year because the region receives significant amounts of rainfall which is easily recharged through the solution channels. Runoff return through solution channels into surface watercourses is sometimes very high. Water levels are typically moderately deep. The limestone serves as a significant source of ground water because of the high hydraulic conductivity of the solution channels. Caves related to this setting are widespread, but their greatest concentration occurs in a band 200-400 miles wide extending from central Missouri through western Virginia.



Setting 6 E Solution Limestone

Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	30-50	5	5	25
Net Recharge	10+	4	9	36
Aquifer Media	Karst Limestone	3	10	30
Soil Media	Thin or Absent	2	10	20
Topography	6-12%	1	5	5
Impact Vadose Zone	Karst Limestone	5	10	50
Hydraulic Conductivity	2000+	3	10	30

DRASTIC Index 196

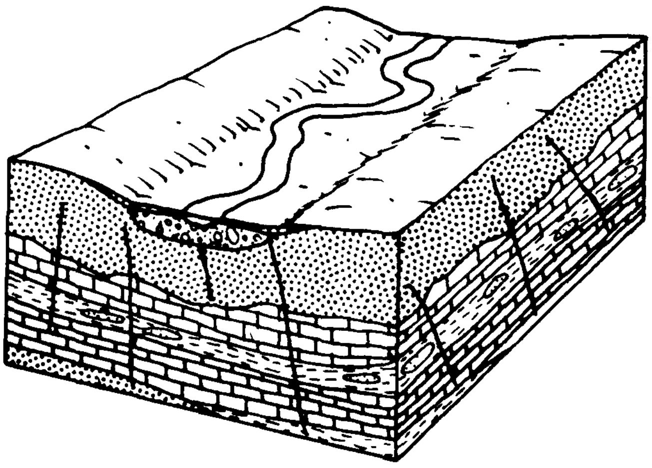
Setting 6 E Solution Limestone

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	10+	4	9	36
Aquifer Media	Karst Limestone	3	10	30
Soil Media	Thin or Absent	5	10	50
Topography	6-12%	3	5	15
Impact Vadose Zone	Karst Limestone	4	10	40
Hydraulic Conductivity	2000+	2	10	20
		Agricultural DRASTIC Index		216

Non-Glaciated Central

(6Fa) River Alluvium With Overbank

This hydrogeologic setting is characterized by low topography and deposits of alluvium along parts of stream valleys. Water is obtained from sand and gravel layers which are interbedded with finer grained alluvial deposits. The floodplain is covered by varying thicknesses of fine grained silt and clay called overbank deposits. The overbank thickness is usually thicker along major streams (commonly as much as 40 feet), and thinner along minor streams. Precipitation varies widely over the region, but recharge is somewhat reduced because of the impermeable nature of the overbank deposits and subsequent clayey loam soils which typically cover the surface. There is usually substantial recharge, however, due to infiltration from the associated stream. Water levels are typically moderately shallow. The alluvium is commonly in direct hydraulic connection with the underlying sedimentary rocks.



Setting 6 Fa River Alluvium With Overbank

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Clay Loam	2	3	6
Topography	0-2%	1	10	10
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	1000-2000	3	8	24
		DRASTIC Index		136

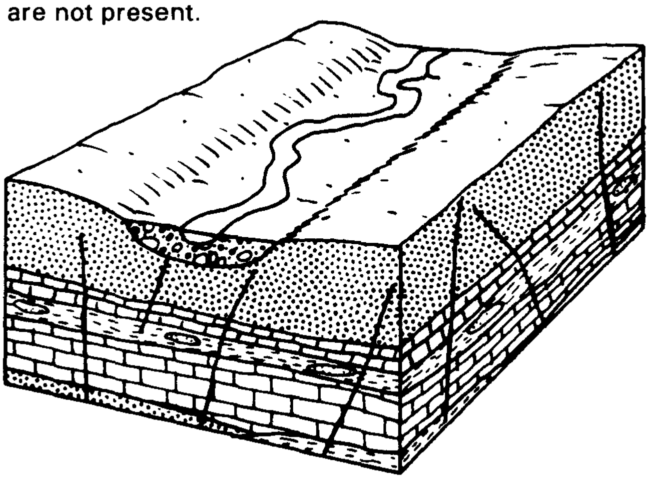
Setting 6 Fa River Alluvium With Overbank

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Clay Loam	5	3	15
Topography	0-2%	3	10	30
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	1000-2000	2	8	16
		Agricultural DRASTIC Index		156

Non-Glaciated Central

(6Fb) River Alluvium Without Overbank

This setting is identical to 6Fa River Alluvium with Overbank except that no significant fine grained floodplain deposits occupy the stream valley. This results in significantly higher recharge where precipitation is adequate and sandy loam soils occur at the surface. Water levels are typically closer to the surface because the fine-grained overbank deposits are not present.



Setting 6 Fb River Alluvium Without Overbank

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	0-2%	1	10	10
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	1000-2000	3	8	24

DRASTIC Index 187

Setting 6 Fb River Alluvium Without Overbank

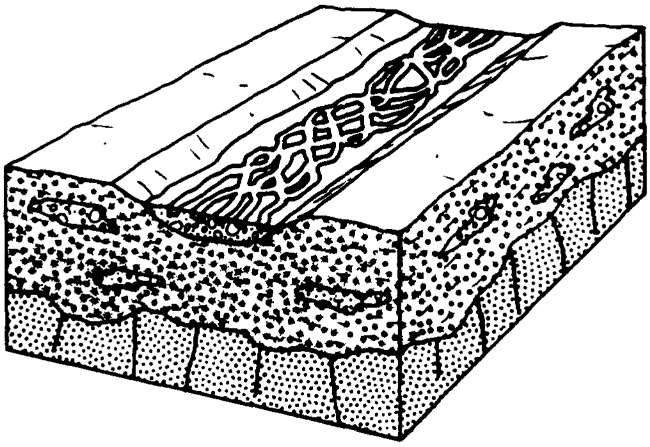
		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	0-2%	3	10	30
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	1000-2000	2	8	16

Agricultural DRASTIC Index 209

Non-Glaciated Central

(6G) Braided River Deposits

This hydrogeologic setting is characterized by deposits of alluvium which occur within the floodplain of streams and rivers. The stream is characterized by a low gradient, wide channel and series of interconnected shallow channels which form a braided pattern. Water levels are typically shallow. This setting is found only in the western portion of this ground-water region. The river alluvium does not serve as a significant source of ground water where it overlies more productive semi-consolidated deposits. However, recharge from the river is substantial and the underlying deposits are in direct hydraulic connection with the overlying alluvium; therefore, the potential for pollution of the aquifer is high. Although precipitation commonly averages less than 20 inches per year, recharge is relatively high due to the flat topography and sandy surficial deposits.



Setting 6 G Braided River Deposits

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	0-5	5	10	50
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	0-2%	1	10	10
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	1000-2000	3	8	24

DRASTIC Index 190

Setting 6 G Braided River Deposits

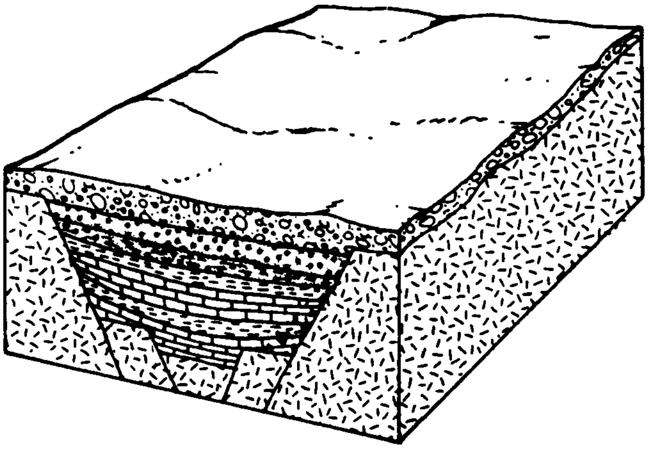
		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	0-5	5	10	50
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	0-2%	3	10	30
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	1000-2000	2	8	16

Agricultural DRASTIC Index 221

Non-Glaciated Central

(6H) Triassic Basins

This hydrogeologic setting is characterized by moderately dipping, highly faulted beds of sandstone, shale, and silty limestone. Conglomeritic deposits occur in some areas. These basins tend to be bounded by high angle faults, with the basins being elongate in the NE-SW directions. The sedimentary beds may be cut by narrow (dikes, etc.) igneous intrusions, and are sometimes indurated by the intrusive activity. The Triassic formations are often red in color due to high iron concentrations, but green colors are also common. These deposits may serve as a localized source of water and water levels are variable.



Setting 6 H Triassic Basins

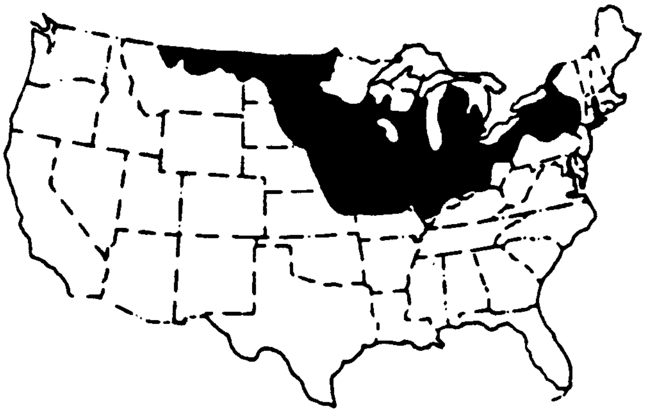
Feature	Range	General Weight	General Rating	General Number
Depth to Water Table	75-100	5	2	10
Net Recharge	4-7	4	6	24
Aquifer Media	Massive Sandstone	3	6	18
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	1-100	3	1	3
		DRASTIC Index		106

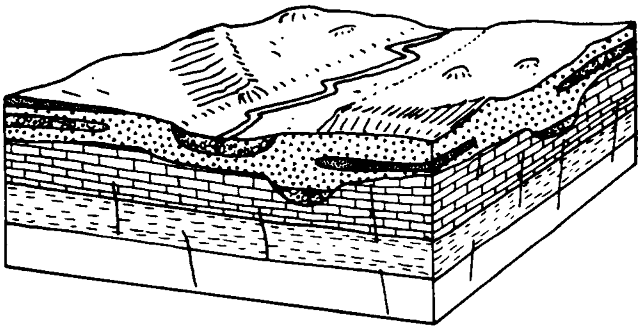
Setting 6 H Triassic Basins

Feature	Range	Agricultural Weight	Agricultural Rating	Agricultural Number
Depth to Water Table	75-100	5	2	10
Net Recharge	4-7	4	6	24
Aquifer Media	Massive Sandstone	3	6	18
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	Bedded LS, SS, SH	4	6.	24
Hydraulic Conductivity	1-100	2	1	2
		Agricultural DRASTIC Index		135

7. *Glaciated Central Region*

(Glacial deposits over fractured sedimentary rocks)





The Glaciated Central region occupies an area of 1,297,000 km^2 extending from the Triassic Basin in Connecticut and Massachusetts and the Catskill Mountains in New York on the east to the northern part of the Great Plains in Montana on the west. The part of the region in New York and Pennsylvania is characterized by rolling hills and low, rounded mountains that reach altitudes of 1,500 m. Westward across Ohio to the western boundary of the region along the Missouri River, the region is flat to gently rolling. Among the more prominent topographic features in this part of the region are low, relatively continuous ridges (moraines) which were formed at the margins of ice sheets that moved southward across the area one or more times during the Pleistocene age.

The Glaciated Central region is underlain by relatively flat-lying consolidated sedimentary rocks that range in age from Paleozoic to Tertiary. They consist primarily of sandstone, shale, limestone, and dolomite. The bedrock is overlain by glacial deposits which, in most of the area, consist chiefly of till, an unsorted mixture of rock particles deposited directly by the ice sheets. The till is interbedded with and overlain by sand and gravel deposited by meltwater streams, by silt and clay deposited in glacial lakes, and, in large parts of the North-Central States, by loess, a well-sorted silt believed to have been deposited primarily by the wind.

On the Catskill Mountains and other uplands in the eastern part of the region, the glacial deposits are typically only a few to several meters thick, but localized deposits as much as 30 m thick are common on southerly slopes. In much of the central and western parts of the region, the glacial deposits exceed 100 m in thickness. The principal exception is the "driftless" area in Wisconsin, Minnesota, Iowa, and Illinois, where the ice, if it invaded the area, was too thin to erode preexisting soils or to deposit a significant thickness of till. Thus, the bedrock in this area is overlain by thin soils derived primarily from weathering of the rock. This area, both geologically and hydrologically, resembles the Nonglaciated Central region and is, therefore, included as part of that region.

The glacial deposits are thickest in valleys in the bedrock surface; thicknesses of 100 to 300 m occur in the valleys of the Finger Lakes in New York. In most of the region westward from Ohio to the Dakotas, the thickness of the glacial deposits exceeds the relief on the preglacial surface, with the result that the locations of valleys and stream channels in the preglacial surface are no longer discernible from the land surface. The glacial deposits in valleys include, in addition to till and lacustrine silts and clays, substantial thicknesses of highly permeable sand and gravel.

Ground water occurs both in the glacial deposits and in the bedrock. Water occurs in the glacial deposits in pores between the rock particles and in the bedrock primarily along fractures. The dominant water-bearing fractures in the bedrock are along bedding planes. Water also occurs in the bedrock in steeply dipping fractures that cut across the beds and, in some sandstones and conglomerates, in primary pores that were not destroyed in the process of cementation and consolidation.

Large parts of the region are underlain by limestones and dolomites in which the fractures have been enlarged by solution. Caves are relatively common in the limestones where the ice sheets were relatively thin, as near the southern boundary of the region and in the "driftless" area. A few caves occur in other parts of the region, notably in the Mohawk River valley in central New York, where they were apparently protected from glacial erosion by the configuration of the bedrock surface over which the ice moved. However, on the whole, caves and other large solution openings, from which large springs emerge and which yield large quantities of water to wells in parts of the Nonglaciated Central region, are much less numerous and hydrologically much less important in the Glaciated Central region.

The glacial deposits are recharged by precipitation on the interstream areas and serve both as a source of water to shallow wells and as a reservoir for recharge to the underlying bedrock. Precipitation ranges from about 400 mm per year in the western part of the region to about 1,000 mm in the eastern part. Recharge also depends on the permeability of the glacial deposits exposed at the land surface and on the slope of the surface. On sloping hillsides underlain by clay-rich till, the annual rate of recharge, even in the humid eastern part of the region, probably does not exceed 50 mm. In contrast, relatively flat areas underlain by sand and gravel may receive as much as 300 mm of recharge annually in the eastern part of the region. Recharge of the ground-water system in the Glaciated Central region occurs primarily in the fall, after plant growth has stopped and cool temperatures have reduced evaporation, and again during the spring thaw before plant growth begins. Of these recharge periods, the spring thaw is usually dominant except when fall rains are unusually heavy. Minor amounts of recharge also may occur during midwinter thaws and during unusually wet summers.

Ground water in small to moderate amounts can be obtained anyplace in the region, both from the glacial deposits and from the bedrock. Large to very large amounts are obtained from the sand and gravel deposits and from some of the limestones, dolomites, and sandstones in the North-Central States. The shales are the least productive bedrock formations in the region.

As is the case in the Nonglaciated Central region, mineralized water occurs at relatively shallow depth in the bedrock in large parts of this region. Because the principal constituent in the mineralized water is sodium chloride (common salt), the water is commonly referred to as saline or salty. The thickness of the freshwater zone in the bedrock depends on the vertical hydraulic conductivity of both the bedrock and the glacial deposits and on the effectiveness of the hydraulic connection between them. Both the freshwater and the underlying saline water move toward the valleys of perennial streams to discharge. As a result, the depth to saline water is less under valleys than under uplands, both because of lower altitudes and because of the upward movement of the saline water to discharge. In those parts of the region underlain by saline water, the concentration of dissolved solids increases with depth. At depths of 500 to 1,000 m in much of the region, the mineral content of the water approaches that of seawater (about 35,000 mg/l). At greater depths, the mineral content may reach concentrations several times that of seawater.

Because the Glaciated Central region resembles in certain aspects both the Nonglaciated Central region (region 6) to the south and the Northeast and Superior Uplands region (region 9) to the north, it may be useful to comment on the principal differences among these three regions. First, and as is already apparent, the bedrock in the Glaciated Central and the Nonglaciated Central regions is similar in composition and structure. The difference in these two regions is in the composition and other characteristics of the overlying unconsolidated material. In the Nonglaciated Central region this material consists of a relatively thin layer that is derived from weathering of the underlying bedrock and that in any particular area is of relatively uniform composition. In the Glaciated Central region, on the other hand, the unconsolidated material consists of a layer, ranging in thickness from a few meters to several hundred meters, of diverse composition deposited either directly from glacial ice (till) or by meltwater streams (glaciofluvial deposits). From a hydrologic standpoint, the unconsolidated material in the Nonglaciated Central region is of minor importance both as a source of water and as a reservoir for storage of water for the bedrock. In contrast, the glacial deposits in the Glaciated Central region serve both as a source of ground water and as an important storage reservoir for the bedrock.

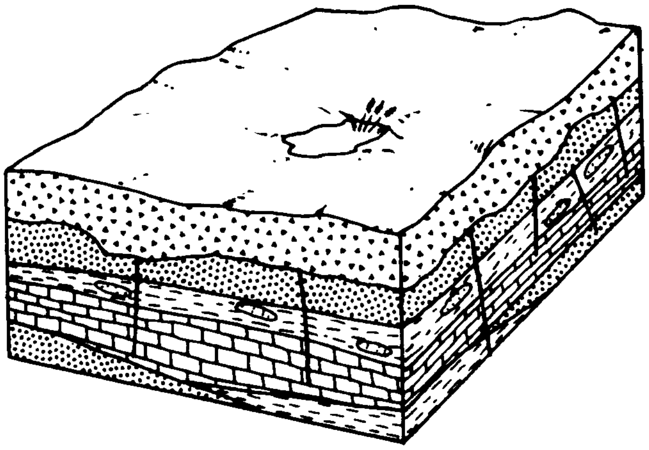
The Glaciated Central region and the Northeast and Superior Uplands region are similar in that the unconsolidated material in both consists of glacial deposits. However, the bedrock in the two regions is different. The bedrock in the Glaciated Central region, as we have already seen, consists of consolidated sedimentary rocks that contain both steeply dipping fractures and fractures along bedding planes. In the Northeast and Superior Uplands, on the other hand, the bedrock is composed of intrusive igneous and metamorphic rocks (nonbedded) in which most water-bearing openings are steeply-dipping fractures. As a result of the differences in fractures, the bedrock in the Glaciated Central region is, in general, a more productive and more important source of ground water than the bedrock in the Northeast and Superior Uplands region.

The largest fresh-water supply in North America, the Great Lakes, is located in this region. Bordering the Great Lakes, there are abandoned beach ridges, present-day beaches and sand dunes, all of which are very sensitive environmental areas.

Glaciated Central

(7Aa) Glacial Till Over Bedded Sedimentary Rocks

This hydrogeologic setting is characterized by low topography and relatively flat-lying, fractured sedimentary rocks consisting of sandstone, shale and limestone which are covered by varying thicknesses of glacial till. The till is chiefly unsorted deposits which may be interbedded with loess or localized deposits of sand and gravel. Although ground water occurs in both the glacial deposits and in the intersecting bedrock fractures, the bedrock is the principal aquifer. The glacial till serves as a source of recharge to the underlying bedrock. Although precipitation is abundant in most of the region, recharge is moderate because of the glacial till and soils which are typically clay loams. Depth to water is extremely variable depending in part on the thickness of the glacial till, but tends to average around 30 feet.



Setting 7 Aa Glacial Till Over Bedded Sedimentary Rock

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	4-7	4	6	24
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Clay Loam	2	3	6
Topography	2-6%	1	9	9
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	100-300	3	2	6
		DRASTIC Index		93

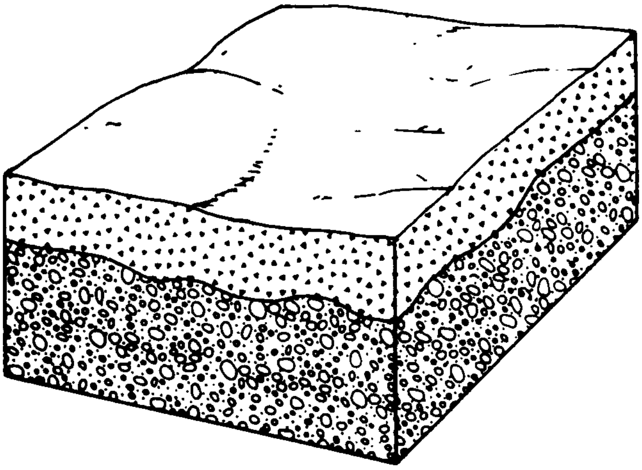
Setting 7 Aa Glacial Till Over Bedded Sedimentary Rock

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	4-7	4	6	24
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Clay Loam	5	3	15
Topography	2-6%	3	9	27
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	100-300	2	2	4
		Agricultural DRASTIC Index		117

Glaciated Central

(7Ab) Glacial Till Over Outwash

This hydrogeologic setting is characterized by low topography and outwash materials which are covered by varying thicknesses of glacial till. The till is chiefly unsorted deposits which may be interbedded with loess or localized deposits of sand and gravel. Surficial deposits have usually weathered to a clay loam. Although ground water occurs in both the glacial deposits and in the underlying outwash, the outwash serves as the principal aquifer because the fine-grained deposits have been removed by glacial meltwater. The outwash is in direct hydraulic connection with the glacial till and glacial till serves as a source of recharge for the underlying outwash. This setting is similar to (7Aa) Glacial Till Over Bedded Sedimentary Rock and (7Ac) Glacial Till Over Solution Limestone in that although precipitation is abundant in most of the region, recharge is moderate because of the relatively low permeability of the overlying glacial till. Depth to water table is extremely variable depending in part on the thickness of the glacial till, but averages around 30 feet.



Setting 7 Ab Glacial Till Over Outwash

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Clay Loam	2	3	6
Topography	2-6%	1	9	9
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	1000-2000	3	8	24

DRASTIC Index 127

Setting 7 Ab Glacial Till Over Outwash

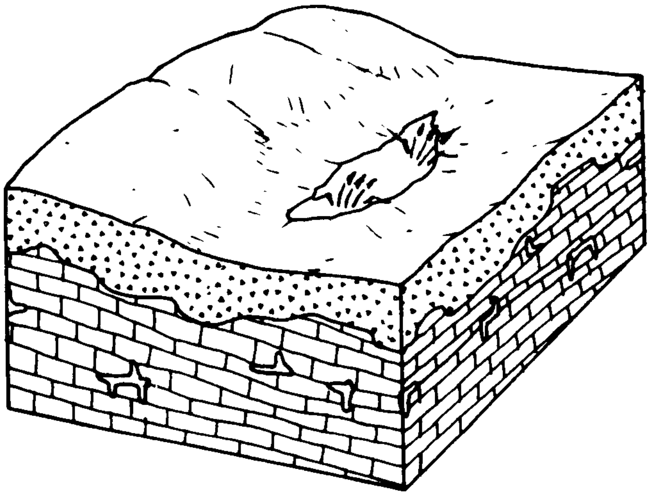
Feature	Range	Agricultural		
		Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Clay Loam	5	3	15
Topography	2-6%	3	9	27
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	1000-2000	2	8	16

Agricultural DRASTIC Index 145

Glaciated Central

(7Ac) Glacial Till Over Solution Limestone

This hydrogeologic setting is characterized by low topography and solution limestone which are covered by varying thicknesses of glacial till. The till is chiefly unsorted deposits which may be interbedded with loess or localized deposits of sand and gravel. Surficial deposits have usually weathered to a clay loam. Although ground water occurs in both the glacial deposits and in the underlying limestone, the limestone, which typically contains solution cavities, serves as the principal aquifer. The limestone is in direct hydraulic connection with the glacial till and the glacial till serves as a source of recharge for the underlying limestone. This setting is similar to (7Aa) Glacial Till Over Bedded Sedimentary Rock and (7Ab) Glacial Till Over Outwash in that although precipitation is abundant in most of the region, recharge is moderate because of the relatively low permeability of the overlying glacial till. Depth to water table is extremely variable depending in part on the thickness of the glacial till, but is typically moderately deep.



Setting 7 Ac Glacial Till Over Solution Limestone

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	4-7	4	6	24
Aquifer Media	Karst Limestone	3	10	30
Soil Media	Clay Loam	2	3	6
Topography	2-6%	1	9	9
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	2000+	3	10	30

DRASTIC Index 129

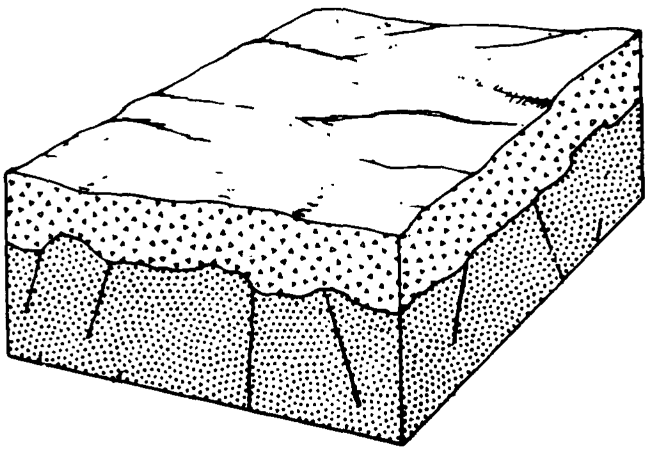
Setting 7 Ac Glacial Till Over Solution Limestone

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	4-7	4	6	24
Aquifer Media	Karst Limestone	3	10	30
Soil Media	Clay Loam	5	3	15
Topography	2-6%	3	9	27
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	2000+	2	10	20
		Agricultural DRASTIC Index		145

Glaciated Central

(7Ad) Glacial Till Over Sandstone

This hydrogeologic setting is characterized by low topography and relatively flat-lying fractured sandstones which are covered by varying thicknesses of glacial till. The till is chiefly unsorted deposits which may be interbedded with loess or localized deposits of sand and gravel. Although ground water occurs in both the glacial deposits and in the intersecting bedrock fractures, the bedrock is the principal aquifer. The glacial till serves as a source of recharge to the underlying bedrock. Although precipitation is abundant in most of the region, recharge is moderate because of the glacial tills which typically weather to clay loam. Depth to water table is extremely variable, depending in part on the thickness of the glacial till, but tends to average around 40 feet.



Setting 7 Ad Glacial Till Over Sandstone

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	4-7	4	6	24
Aquifer Media	Massive Sandstone	3	6	18
Soil Media	Clay Loam	2	3	6
Topography	2-6%	1	9	9
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	300-700	3	4	12
		DRASTIC Index		99

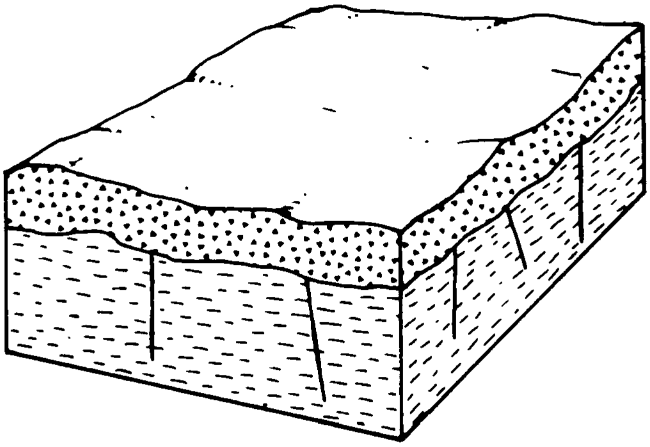
Setting 7 Ad Glacial Till Over Sandstone

		Agricultural		
. Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	4-7	4	6	24
Aquifer Media	Massive Sandstone	3	6	18
Soil Media	Clay Loam	5	3	15
Topography	2-6%	3	9	27
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	300-700	2	4	8
		Agricultural DRASTIC Index		121

Glaciated Central

(7Ae) Glacial Till Over Shale

This hydrogeologic setting is similar to (7Ad) Glacial Till Over Sandstone except that varying thickness of till overlie fractured flat-lying shales. The till is chiefly unsorted deposits with interbedded lenses of loess and sand and gravel. Ground water is derived from either localized sources in the overlying till or from deeper, more permeable formations. The shale is relatively impermeable and does not serve as a source of ground water. Although precipitation is abundant, recharge is minimal from the till to deeper formations and occurs only by leakage of water through the fractures.



Setting 7 Ae Glacial Till Over Shale

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	4-7	4	6	24
Aquifer Media	Massive Shale	3	2	6
Soil Media	Clay Loam	2	3	6
Topography	2-6%	1	9	9
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	1-100	3	1	3

DRASTIC Index 78

Setting 7 Ae Glacial Till Over Shale

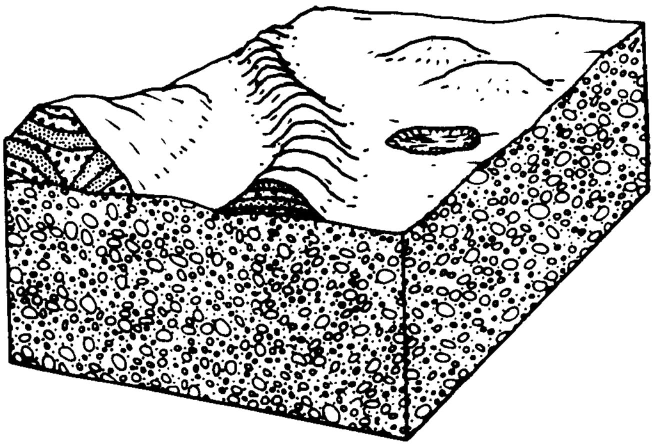
Feature	Range	Agricultural		
		Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	4-7	4	6	24
Aquifer Media	Massive Shale	3	2	6
Soil Media	Clay Loam	5	3	15
Topography	2-6%	3	9	27
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	1-100	2	1	2

Agricultural DRASTIC Index 103

Glaciated Central

(7Ba) Outwash

This hydrogeologic setting is characterized by moderate to low topography and varying thicknesses of outwash which overlie sequences of fractured sedimentary rocks. The outwash consists of water-washed deposits of sand and gravel which serve as the principal aquifer in the area. The outwash also serves as a source of recharge to the underlying bedrock. Precipitation is abundant throughout most of the area and recharge is moderate to high. Recharge is somewhat restricted by the sandy loam soil which typically develops in this setting. Water levels are extremely variable but relatively shallow. Outwash generally refers to water washed or ice contact deposits, and can include a variety of morphogenic forms. Outwash plains are thick sequences of sands and gravels that are laid down in sheet-like deposits from sediment laden waters draining off, and from within a glacier. These deposits are well sorted and have relatively high permeabilities. Kames and eskers are ice-contact deposits. A kame is an isolated hill or mound of stratified sediments deposited in an opening within or between ice blocks, or between ice blocks and valley walls. An esker is a sinuous or meandering ridge of well sorted sands and gravels that are remnants of streams that existed beneath and within the glaciers. These deposits may be in direct hydraulic connection with underlying fractured bedrock.



Setting 7 Ba Outwash

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	1000-2000	3	8	24

DRASTIC Index 176

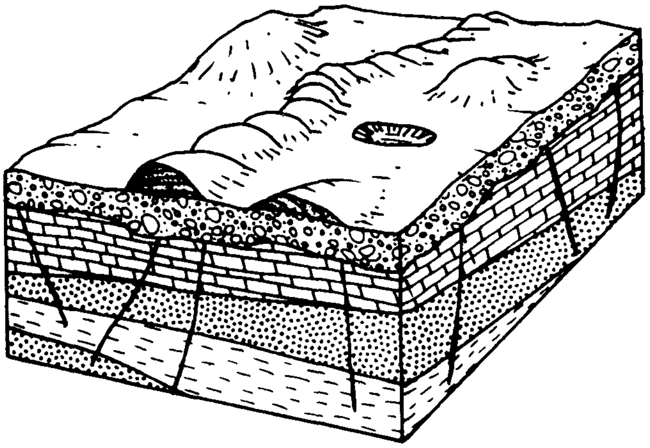
Setting 7 Ba Outwash

Feature	Range	Agricultural		
		Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	1000-2000	2	8	16
		Agricultural DRASTIC Index		196

Glaciated Central

(7Bb) Outwash Over Bedded Sedimentary

This hydrogeologic setting is characterized by moderate to low topography and relatively flat-lying, fractured sedimentary rocks consisting of sandstones, shales, and limestone which are covered by varying thicknesses of glacial outwash. The outwash consists of a variety of water-washed deposits of sand and gravel which serve as the principal aquifer in the areas. The outwash also serves as a source of recharge to the underlying bedrock. Precipitation is abundant throughout most of the area and recharge is moderate to high. Water levels are extremely variable, but typically shallow.



Setting 7 Bb Outwash Over Bedded Sedimentary

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	10+	4	9	36
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	100-300	3	2	6
		DRASTIC Index		156

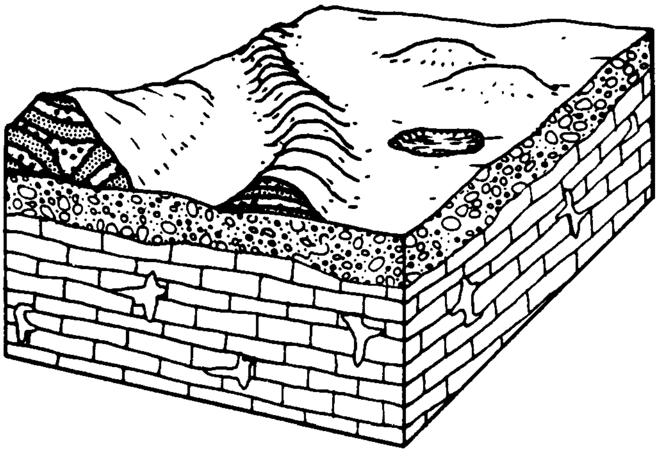
Setting 7 Bb Outwash Over Bedded Sedimentary

Feature	Range	Agricultural		
		Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	10+	4	9	36
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	100-300	2	2	4
		Agricultural DRASTIC Index		182

Glaciated Central

(7Bc) Outwash Over Solution Limestone

This hydrogeologic setting is characterized by low topography and solution limestone which is covered by varying thicknesses of glacial outwash. The outwash consists of varying types of water-washed deposits that typically weather to sandy loam soils. Both the outwash and the solution limestone serve as principal aquifers in the area. The solution limestone is in direct hydraulic connection with the glacial outwash and the outwash serves as a source of recharge for the underlying limestone. Water levels are extremely variable and in part dependent on the thickness of the overlying outwash.



Setting 7 Bc Outwash Over Solution Limestone

Feature	Range	General Weight	General Rating	General Number
Depth to Water Table	15-30	5	7	35
Net Recharge	10+	4	9	36
Aquifer Media	Karst Limestone	3	10	30
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	1000-2000	3	8	24

DRASTIC Index 186

Setting 7 Bc Outwash Over Solution Limestone

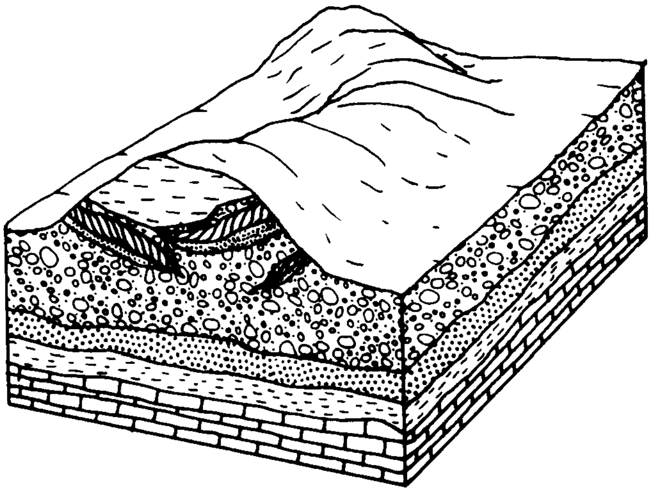
Feature	Range	Agricultural Weight	Agricultural Rating	Agricultural Number
Depth to Water Table	15-30	5	7	35
Net Recharge	10+	4	9	36
Aquifer Media	Karst Limestone	3	10	30
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	1000-2000	2	8	16

Agricultural DRASTIC Index 206

Glaciated Central

(7C) Moraine

This hydrogeologic setting is characterized by moderate to moderately steep topography and varying thicknesses of mixed glacial deposits which overlie sequences of relatively flat-lying fractured sedimentary rocks. This setting is similar to (7Ba) Outwash in that the sand and gravel within the morainal deposits may be well-sorted and serve as the principal aquifer in the area. These deposits also serve as a source of recharge for the underlying bedrock. Moraines also contain sediments that are typically unsorted and unstratified; these deposits contain more fines than outwash deposits, are less permeable and characteristic of glacial till. Moraines are typically mounds or ridges of till which were deposited along the margin of a stagnant or retreating glacier. Surficial deposits often weather to a sandy loam. Precipitation is abundant throughout the region and ground-water recharge is moderate. Water levels are extremely variable, based in part on the thickness of the glacial till, but are typically fairly shallow.



Setting 7 C Moraine

Feature	Range	General Weight	General Rating	General Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	6-12%	1	5	5
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	300-700	3	4	12

DRASTIC Index 125

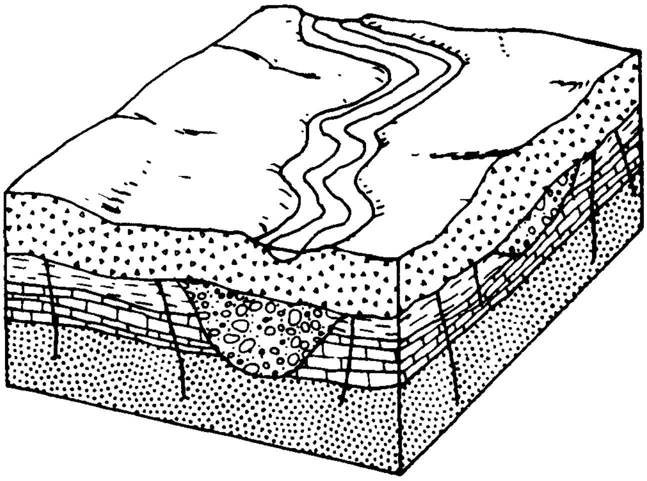
Setting 7 C Moraine

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	6-12%	3	5	15
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	300-700	2	4	8
		Agricultural DRASTIC Index		148

Glaciated Central

(7D) Buried Valley

This hydrogeologic setting is characterized by thick deposits of sand and gravel that have been deposited in a former topographic low (usually a pre-glacial river valley) by glacial meltwaters. These deposits are capable of yielding large quantities of ground water. The deposits may or may not underlie a present-day river and may or may not be in direct hydraulic connection with a stream. Glacial till or recent alluvium often overlies the buried valley. Usually the deposits are several times more permeable than the surrounding bedrock, with finer grained alluvium covering the underlying sand and gravel. Soils are typically a sandy loam. Recharge to the sand and gravel is moderate and water levels are commonly relatively shallow, although they may be quite variable.



Setting 7 D Buried Valley

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	S & G w/sig Silt and Clay	5	6	30
Hydraulic Conductivity	1000-2000	3	8	24
		DRASTIC Index		156

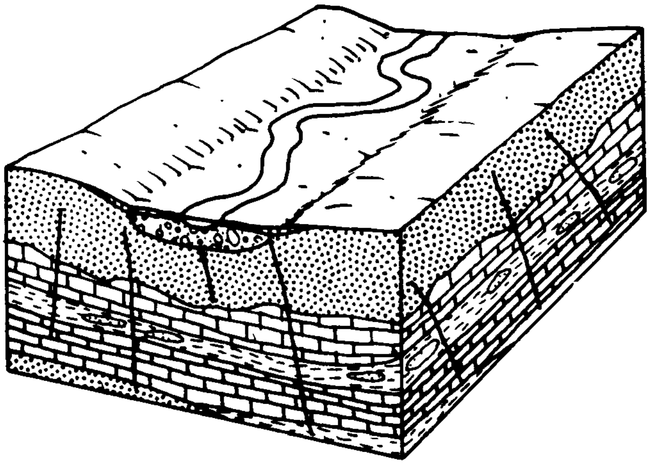
Setting 7 D Buried Valley

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	S & G w/sig. Silt and Clay	4	6	24
Hydraulic Conductivity	1000-2000	2	8	16
		Agricultural DRASTIC Index		178

Glaciated Central

(7Ea) River Alluvium With Overbank Deposits

This hydrogeologic setting is characterized by low topography and thin to moderately thick deposits of flood deposited alluvium along portions of the river valley. The alluvium is underlain by fractured bedrock of sedimentary, metamorphic, or igneous origin. Water is obtained from sand and gravel layers which are interbedded with finer-grained alluvial deposits. The floodplain is covered by varying thicknesses of fine-grained silt and clay called overbank deposits. The overbank thickness is usually greater along major streams (as much as 40 feet) and thinner along minor streams. Precipitation in the region varies, but recharge is somewhat reduced because of the silty and clayey overbank soils which typically cover the surface. Water levels are moderately shallow. Ground water is in direct hydraulic contact with the surface stream. The alluvium may serve as a significant source of water and may also be in direct hydraulic contact with the underlying sedimentary rocks.



Setting 7 Ea River Alluvium With Overbank Deposit

Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Silty Loam	2	4	8
Topography	0-2%	1	10	10
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	700-1000	3	6	18
		DRASTIC Index		124

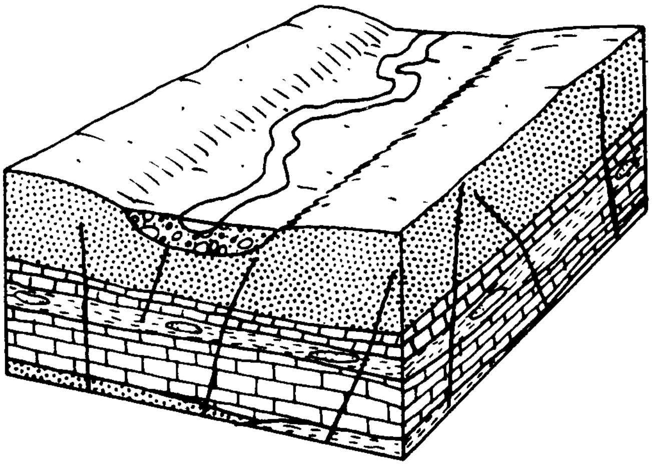
Setting 7 Ea River Alluvium With Overbank Deposit

Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Silty Loam	5	4	20
Topography	0-2%	3	10	30
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	700-1000	2	6	12
		Agricultural DRASTIC Index		149

Glaciated Central

(7Eb) River Alluvium Without Overbank

This setting is identical to (6Fa) River Alluvium with Overbank except that no significant fine-grained floodplain deposits occupy the stream valley. This results in significantly higher recharge where precipitation is adequate and sandy soils occur at the surface. Water levels are moderate to shallow in depth. Hydraulic contact with the surface stream is usually excellent, with alternating recharge/discharge relationships varying with stream stage. These deposits also serve as a good source of recharge to the underlying fractured bedrock.



Setting 7 Eb River Alluvium Without Overbank Deposit

Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	0-2%	1	10	10
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	700-1000	3	6	18
		DRASTIC Index		191

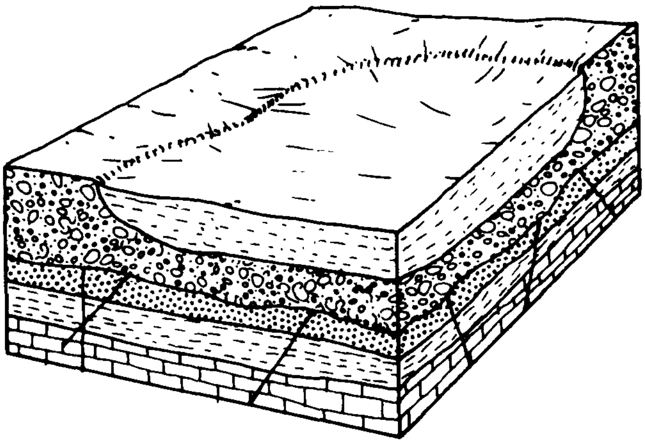
Setting 7 Eb River Alluvium Without Overbank Deposit

Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	0-2%	3	10	30
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	700-1000	2	6	12
		Agricultural DRASTIC Index		224

Glaciated Central

(7F) Glacial Lake Deposits

This hydrogeologic setting is characterized by flat topography and varying thicknesses of fine-grained sediments that overlie sequences of fractured sedimentary rocks. The deposits are composed of fine-grained silts and clays interlayered with fine sand that settled out in glacial lakes and exhibit alternating layers relating to seasonal fluctuations. As a consequence of the thin alternating layers there is a substantial difference between the vertical and horizontal permeability with the horizontal commonly two or more orders of magnitude greater than the vertical. Due to their fine-grained nature, these deposits typically weather to organic-rich sandy loams with a range in permeabilities reflecting variations in sand content. Underlying glacial deposits or bedrock serve as the major source of ground water in the region. Although precipitation is abundant, recharge is controlled by the permeability of the surface clays, however, in all instances recharge is moderately high because of the impact of the low topography. Water levels are variable, depending on the thickness of the lake sediments and the underlying materials.



Setting 7 F Glacial Lake Deposits

Feature	Range	General Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	2	6	12
Topography	0-2%	1	10	10
Impact Vadose Zone	S & G w/sig. Silt and Clay	5	6	30
Hydraulic Conductivity	100-300	3	2	6
		DRASTIC Index		135

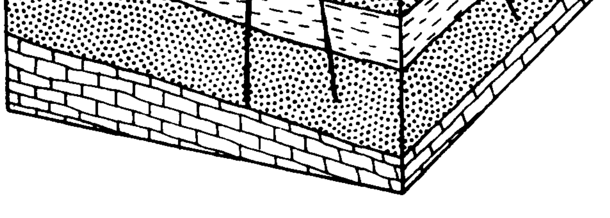
Setting 7 F Glacial Lake Deposits

Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	4-7	4	6	24
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	5	6	30
Topography	0-2%	3	10	30
Impact Vadose Zone	S & G w/sig. Silt and Clay	4	6	24
Hydraulic Conductivity	100-300	2	2	4
		Agricultural DRASTIC Index		165

Glaciated Central

(7G) Thin Till Over Bedded Sedimentary

This hydrogeologic setting is characterized by moderate to low topography and deposits of thin, patchy, glacial till overlying alternating layers of fractured consolidated sedimentary rocks. The till, where present, is primarily unsorted deposits of clay, sand, and gravel. Although ground water occurs in both the till and in the intersecting fractures of the bedrock, the bedrock is the principal aquifer. The glacial till serves as a source of recharge to the underlying bedrock. Although precipitation is abundant in most of the region, recharge is moderate because of the glacial tills and clayey soils. Water levels are extremely variable, but usually moderate.



Setting 7 G Thin Till Over Bedded Sedimentary

Feature	Range	General Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Clay Loam	2	3	6
Topography	2-6%	1	9	9
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	100-300	3	2	6

DRASTIC Index 111

Setting 7 G Thin Till Over Bedded Sedimentary

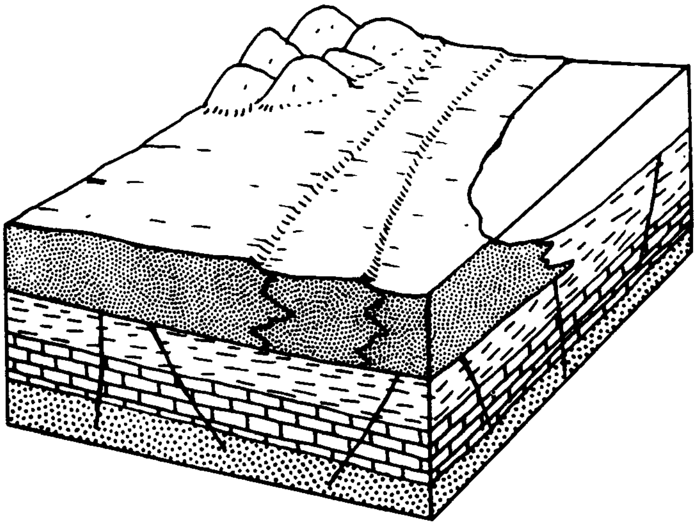
Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Clay Loam	5	3	15
Topography	2-6%	3	9	27
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	100-300	2	2	4

Agricultural DRASTIC Index 135

Glaciated Central

(7H) Beaches, Beach Ridges, and Sand Dunes

This hydrogeologic setting is characterized by low relief, sandy surface soil that is predominantly silica sand, extremely high infiltration rates and low sorptive capacity in the thin vadose zone. The water table is very shallow beneath the beaches bordering the Great Lakes. These beaches are commonly groundwater discharge areas. The water table is slightly deeper beneath the rolling dune topography and the vestigial inland beach ridges. All of these areas serve as recharge sources for the underlying sedimentary bedrock aquifers, and they often serve as local sources of water supply.



Setting 7 H Beaches, Beach Ridges and Sand Dunes

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

DRASTIC Index 202

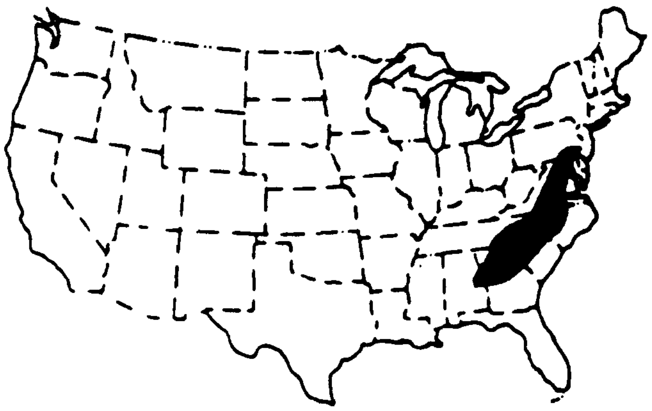
Setting 7 H Beaches, Beach Ridges and Sand Dunes

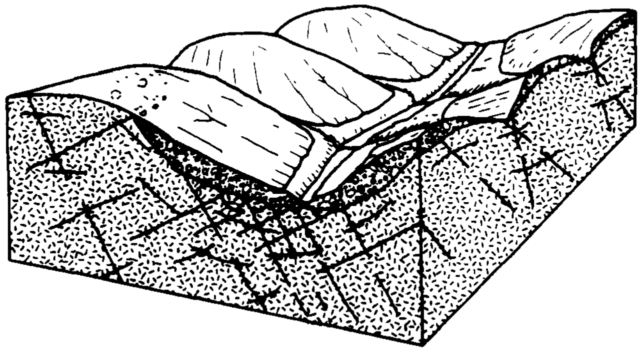
Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	0-5	5	10	50
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	0-2%	3	10	30
Impact Vadose Zone	Sand and Gravel	4	8	24
Hydraulic Conductivity	1000-2000	2	8	16

Agricultural DRASTIC Index 225

8. *Piedmont Blue Ridge Region*

(Thick regolith over fractured crystalline and metamorphosed sedimentary rocks)





The Piedmont and Blue Ridge region is an area of about 247,000 km^2 extending from Alabama on the south to Pennsylvania on the north. The Piedmont part of the region consists of low, rounded hills and long, rolling, northeast-southwest trending ridges whose summits range from about a 100 meters above sea level along its eastern boundary with the Coastal Plain to 500 to 600 m along its boundary with the Blue Ridge area to the west. The Blue Ridge is mountainous and includes the highest peaks east of the Mississippi. The mountains, some of which reach altitudes of more than 2,000 m, have smooth-rounded outlines and are bordered by well-graded streams flowing in relatively narrow valleys.

The Piedmont and Blue Ridge region is underlain by bedrock of Precambrian and Paleozoic age consisting of igneous and metamorphosed igneous and sedimentary rocks. These include granite, gneiss, schist, quartzite, slate, marble, and phyllite. The land surface in the Piedmont and Blue Ridge is underlain by clay-rich, unconsolidated material derived from *in situ* weathering of the underlying bedrock. This material, which averages about 10 to 20 m in thickness and may be as much as 100 m thick on some ridges, is referred to as saprolite. In many valleys, especially those of larger streams, flood plains are underlain by thin, moderately well-sorted alluvium deposited by the streams. When the distinction between saprolite and alluvium is not important, the term regolith is used to refer to the layer of unconsolidated deposits.

The regolith contains water in pore spaces between rock particles. The bedrock, on the other hand, does not have any significant intergranular porosity. It contains water, instead, in sheetlike openings formed along fractures (that is, breaks in the otherwise "solid" rock). The hydraulic conductivities of the regolith and the bedrock are similar and range from about 0.001 to 1 m day^{-1}. The major difference in their water-bearing characteristics is their porosities, that of regolith being about 20 to 30 percent and that of the bedrock about 0.01 to 2 percent. Small supplies of water adequate for domestic needs can be obtained from the regolith through large-diameter bored or dug wells. However, most wells, especially those where moderate supplies of water are needed, are relatively small in diameter and are cased through the regolith and finished with open holes in the bedrock. Although, as noted, the hydraulic conductivity of the bedrock is similar to that of the regolith, bedrock wells generally have much larger yields than regolith wells because, being deeper, they have a much larger available drawdown.

All ground-water systems function both as reservoirs that store water and as pipelines (or conduits) that transmit water from recharge areas to discharge areas. The yield of bedrock wells in the Piedmont and Blue Ridge region depends on the number and size of fractures penetrated by the open hole and on the replenishment of the fractures by seepage into them from the overlying regolith. Thus, the ground-water system in this region can be viewed, from the standpoint of ground-water development, as a terrane in which the reservoir and pipeline functions are effectively separated. Because of its larger porosity, the regolith functions as a reservoir which slowly feeds water downward into the fractures in the bedrock. The fractures serve as an intricate interconnected network of pipelines that transmit water either to springs or streams or to wells.

Recharge of the ground-water system occurs on the areas above the flood plains of streams, and natural discharge occurs as seepage springs that are common near the bases of slopes and as seepage into streams. With respect to recharge conditions, it is important to note that forested areas, which include most of the Blue Ridge and much of the Piedmont, have thick and very permeable soils overlain by a thick layer of forest litter. In these areas, even on steep slopes, most of the precipitation seeps into the soil zone, and most of this moves laterally through the soil in a thin, temporary, saturated zone to surface depressions or streams to discharge. The remainder seeps into the regolith below the soil zone, and much of this ultimately seeps into the underlying bedrock.

Because the yield of bedrock wells depends on the number of fractures penetrated by the well, the key element in selecting well sites is recognizing the relation between the present surface topography and the location of fractures in the bedrock. Most of the valleys, draws, and other surface depressions indicate the presence of more intensely fractured zones in the bedrock which are more susceptible to weathering and erosion than are the intervening areas. Because fractures in the bedrock are the principal avenues along which ground water moves, the best well sites appear to be in draws on the sides of the valleys of perennial streams where the bordering ridges are underlain by substantial thicknesses of regolith. Wells located at such sites seem to be most effective in penetrating open water-bearing fractures and in intercepting ground water draining from the regolith. Chances of success seem to be somewhat less for wells on the flood plains of perennial streams, possibly because the alluvium obscures the topographic expression of bedrock fractures. The poorest sites for wells are on the tops of ridges and mountains where the regolith cover is thin or absent and the bedrock is sparsely fractured.

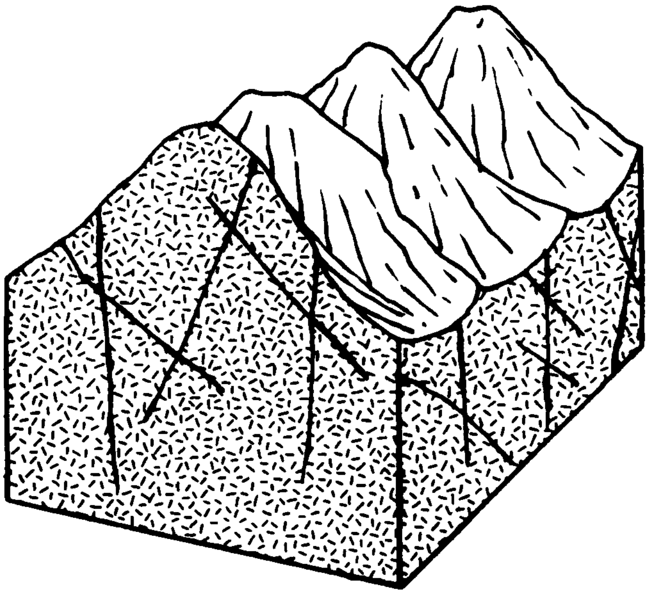
As a general rule, fractures near the bedrock surface are most numerous and have the largest openings, so that the yield of most wells is not increased by drilling to depths greater than about 100 m. Exceptions to this occur in Georgia, South Carolina, and North Carolina and some other areas where water-bearing, low-angle faults or fractured zones are present at depths as great as 200 to 300 m.

The Piedmont and Blue Ridge region has long been known as an area generally unfavorable for ground-water development. This reputation seems to have resulted both from the small reported yields of the numerous domestic wells in use in the region that were, generally, sited as a matter of convenience and from a failure to apply existing technology to the careful selection of well sites where moderate yields are needed. As water needs in the region increase and as reservoir sites on streams become increasingly more difficult to obtain, it will be necessary to make more intensive use of ground water.

Piedmont and Blue Ridge

(8A) Mountain Slopes

This hydrogeologic setting is characterized by steep slopes on the side of mountains, a thin soil cover and fractured bedrock. Ground water is obtained primarily from the fractures in the bedrock which may be of sedimentary, metamorphic, or igneous origin but which is commonly metamorphic or igneous. The fractures provide localized sources of ground water and well yields are typically limited. Although precipitation is abundant, due to the steep slopes, thin soil cover and small storage capacity of the fractures, runoff is significant and ground-water recharge is only moderate. Water levels are extremely variable but are commonly deep.



Setting 8 A Mountain Slopes

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	2-4	4	3	12
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	2	10	20
Topography	18+	1	1	1
Impact Vadose Zone	Metamorphic/ Igneous	5	4	20
Hydraulic Conductivity	1-100	3	1	3
		DRASTIC Index		75

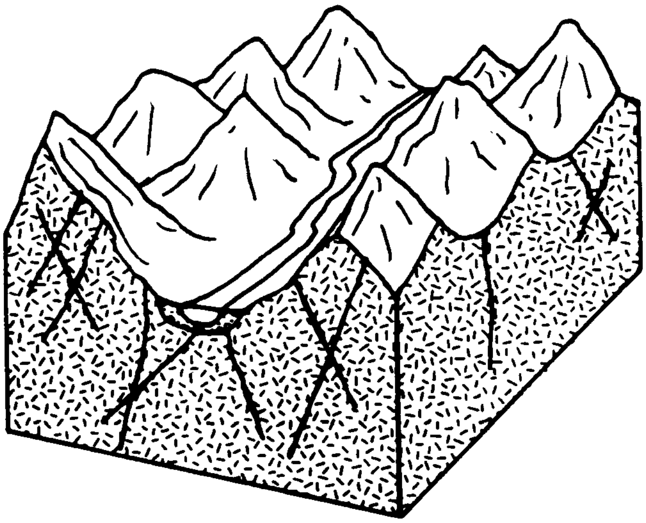
Setting 8 A Mountain Slopes

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	2-4	4	3	12
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	5	10	50
Topography	18+	3	1	3
Impact Vadose Zone	Metamorphic/ Igneous	4	4	16
Hydraulic Conductivity	1-100	2	1	2
		Agricultural DRASTIC Index		102

Piedmont and Blue Ridge

(8B) Alluvial Mountain Valleys

This hydrogeologic setting is characterized by thin bouldery alluvium which overlies fractured bedrock of sedimentary, metamorphic, or igneous origin. The alluvium, which includes both mass-wastage and water-sorted debris, is derived from the surrounding slopes, and serves as a localized source of water. Water is obtained from sand and gravel layers which are interspersed between finer-grained deposits. Surficial deposits have typically weathered to a loam. Water levels are usually relatively shallow but are extremely variable. Ground water is also obtained from the fractures in the underlying bedrock, which are typically in direct hydraulic connection with the overlying alluvium.



Setting 8 B Alluvial Mountain Valleys

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Loam	2	5	10
Topography	2-6%	1	9	9
Impact Vadose Zone	S & G w/sig. Silt and Clay	5	6	30
Hydraulic Conductivity	300-700	3	4	12
		DRASTIC Index		162

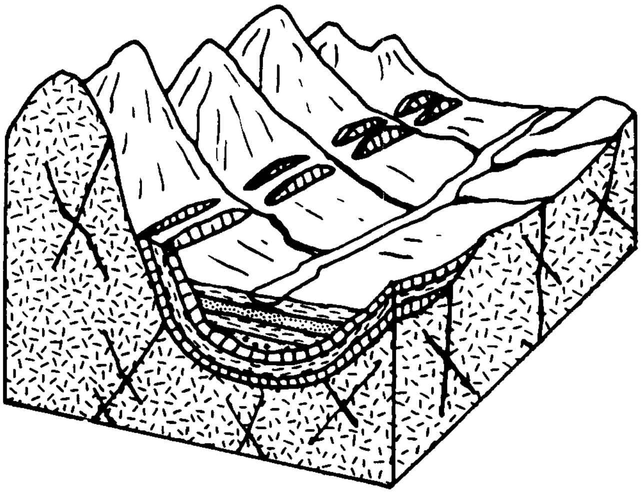
Setting 8 B Alluvial Mountain Valleys

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Loam	5	5	25
Topography	2-6%	3	9	27
Impact Vadose Zone	S & G w/sig. Silt and Clay	4	6	24
Hydraulic Conductivity	300-700	2	4	8
		Agricultural DRASTIC Index		185

Piedmont and Blue Ridge

(8C) Mountain Flanks

This hydrogeologic setting is characterized by moderate topographic relief and moderately-dipping, fractured, consolidated sedimentary rocks. Soil cover is usually thicker than on the mountain slopes and typically has weathered to a sandy loam or loam. Although precipitation is abundant, ground-water recharge is moderate due to the soil cover and slope. Water levels are typically moderately-deep although they are extremely variable. The mountain flanks serve as the recharge area for aquifers which are typically confined in adjacent valley areas.



Setting 8 C Mountain Flanks

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	2-4	4	3	12
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Loam	2	5	10
Topography	6-12%	1	5	5
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	100-300	3	2	6

DRASTIC Index 106

Setting 8 C Mountain Flanks

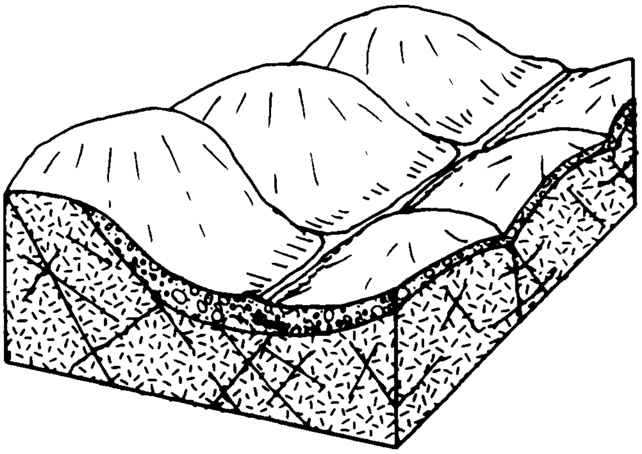
		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	2-4	4	3	12
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Loam	5	5	25
Topography	6-12%	3	5	15
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	100-300	2	2	4

Agricultural DRASTIC Index 123

Piedmont and Blue Ridge

(8D) Thick Regolith

This hydrogeologic setting is characterized by moderate to low slopes covered by thick regolith and underlain by fractured bedrock of igneous, sedimentary, or metamorphic origin. The regolith is typically clay-rich but may also serve as a source of ground water for low-yield wells. This regolith functions as a reservoir for ground-water recharge to the bedrock which is in direct hydraulic connection with the overlying regolith. The bedrock typically yields larger amounts of ground water than the regolith when the well intersects fractures in the bedrock.



Setting 8 D Thick Regolith

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	4-7	4	6	24
Aquifer Media	Weathered Meta./Ig.	3	4	12
Soil Media	Clay Loam	2	3	6
Topography	6-12%	1	5	5
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	1-100	3	1	3

DRASTIC Index 100

Setting 8 D Thick Regolith

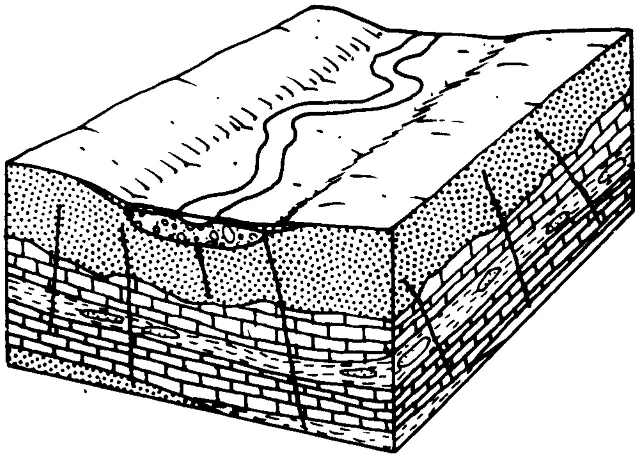
Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	4-7	4	6	24
Aquifer Media	Weathered Meta./Ig.	3	4	12
Soil Media	Clay Loam	5	3	15
Topography	6-12%	3	5	15
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	1-100	2	1	2

Agricultural DRASTIC Index 117

Piedmont and Blue Ridge

(8E) River Alluvium

This hydrogeologic setting is characterized by low topography and deposits of varying thickness of alluvium along parts of stream valleys. The alluvium is underlain by fractured igneous, metamorphic, or consolidated sedimentary rocks. Water is obtained from sand and gravel which is overlain and interbedded with finer-grained alluvial deposits. Surficial deposits usually weather to a sandy loam. The sand and gravel within the alluvium serves as the principal aquifer, but the alluvium also serves as the source of ground-water recharge for the underlying aquifer. Precipitation is abundant and recharge is moderately high, limited only by the loamy surficial deposits. Water levels are extremely variable, but are typically moderately shallow.



Setting 8 E River Alluvium

Feature	Range	General Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	S & G w/sig. Silt and Clay	5	6	30
Hydraulic Conductivity	1000-2000	3	8	24

DRASTIC Index 176

Setting 8 E River Alluvium

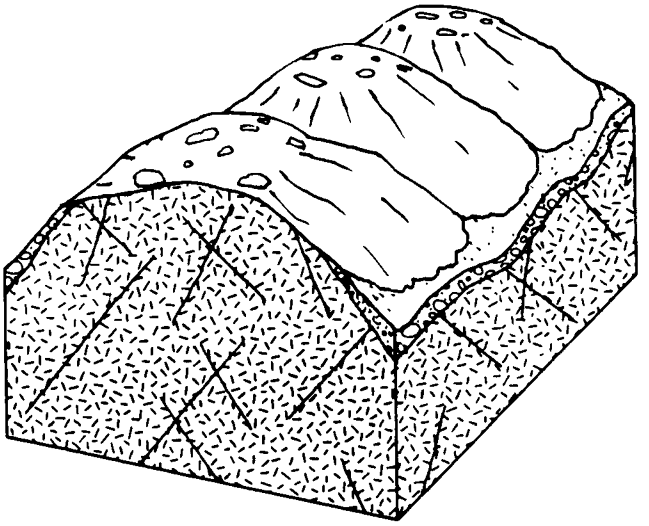
Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	S & G w/sig. Silt and Clay	4	6	24
Hydraulic Conductivity	1000-2000	2	8	16

Agricultural DRASTIC Index 198

Piedmont and Blue Ridge

(8F) Mountain Crests

This hydrogeologic setting is characterized by moderate to steep topography on the crests of mountains with thin soil cover and exposed fractured bedrock. Ground water is obtained primarily from the fractures in the bedrock which may be of sedimentary, metamorphic, or igneous origin but which is commonly metamorphic or igneous. The fractures provide localized sources of ground water and well yields are typically limited. Although precipitation is abundant, due to the slopes, thin soil cover, and small storage capacity of the fractures, runoff is significant and ground-water recharge is low. Water levels are extremely variable but commonly deep.



Setting 8 F Mountain Crests

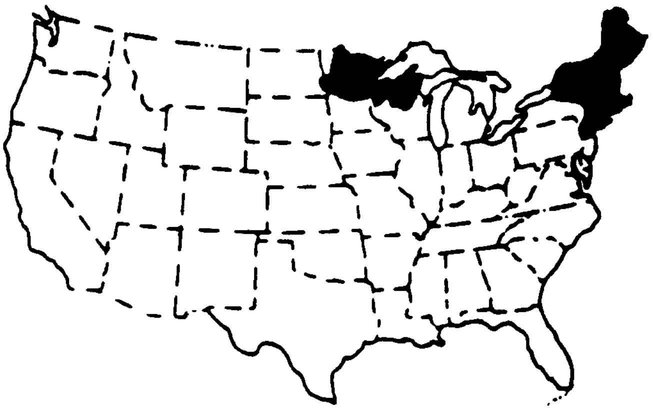
Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	100+	5	1	5
Net Recharge	0-2	4	1	4
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	2	10	20
Topography	2-6%	1	9	9
Impact Vadose Zone	Metamorphic/ Igneous	5	4	20
Hydraulic Conductivity	1-100	3	1	3
		DRASTIC Index		70

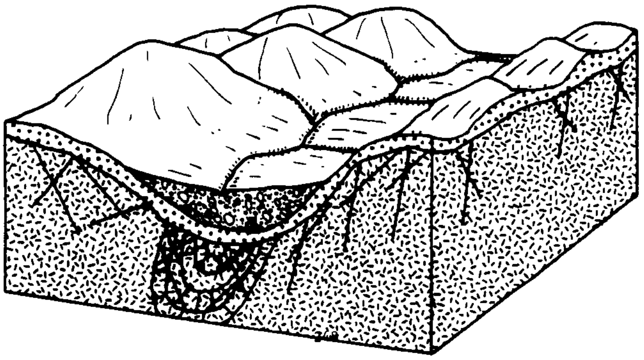
Setting 8 F Mountain Crests

Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	100+	5	1	5
Net Recharge	0-2	4	1	4
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	5	10	50
Topography	2-6%	3	9	27
Impact Vadose Zone	Metamorphic/ Igneous	4	4	16
Hydraulic Conductivity	1-100	2	1	2
		Agricultural DRASTIC Index		113

9. *Northeast and Superior Uplands*

(Glacial deposits over fractured crystalline rocks)





The Northeast and Superior Uplands region is made up of two separate areas totaling about 415,000 km^2. The Northeast Upland encompasses the Adirondack Mountains, the Lake Champlain valley, and nearly all of New England. The parts of New England not included are the Cape Cod area and nearby islands, which are included in the Atlantic and Gulf Coastal Plain region, and the Triassic lowland along the Connecticut River in Connecticut and Massachusetts, which is included in the Glaciated Central region. The Superior Upland encompasses most of the northern parts of Minnesota and Wisconsin adjacent to the western end of Lake Superior. The Northeast and Superior Uplands are characterized by rolling hills and low mountains. Land-surface altitudes in the Northeast Upland range from sea level to more than 1,500 m on some of the peaks in the Adirondacks and White Mountains. In contrast to the mountainous areas in the Northeast, the Superior Upland is in an area of rolling hills whose summits reach altitudes of only 300 to 600 m.

Bedrock in the region ranges in age from Precambrian to Paleozoic and consists mostly of granite, syenite, anorthosite, and other intrusive igneous rocks and metamorphosed sedimentary rocks consisting of gneiss, schist, quartzite, slate, and marble. Most of the igneous and metamorphosed sedimentary rocks have been intensely folded and cut by numerous faults.

The bedrock is overlain by unconsolidated deposits laid down by ice sheets that covered the areas one or more times during the Pleistocene and by gravel, sand, silt, and clay laid down by meltwater streams and in lakes that formed during the melting of the ice. The thickness of the glacial deposits ranges from a few meters on the higher mountains, which also have large expanses of barren rock, to more than 100 m in some valleys. The most extensive glacial deposit is till, which was laid down as a nearly continuous blanket by the ice, both in valleys and on the uplands. In most of the valleys and other low areas, the till is covered by glacial outwash consisting of interlayered sand and gravel, ranging in thickness from a few meters to more than 20 m, that was deposited by streams supplied by glacial meltwater. In several areas, including parts of the Champlain valley and the lowlands adjacent to Lake Superior, the unconsolidated deposits consist of clay and silt deposited in lakes that formed during the melting of the ice sheets.

Ground-water supplies are obtained in the region from both the glacial deposits and the underlying bedrock. The largest yields come from the sand and gravel deposits, which in parts of the valleys of large streams are as much as 60 m thick. Other sand and gravel deposits, not thick or productive enough to be included in the Alluvial Valleys region, occur locally in most valley and lowland areas in the Northeast and Superior Uplands region and serve as important sources of water.

Water occurs in the bedrock in fractures similar in origin, occurrence, and hydraulic characteristics to those in the Piedmont and Blue Ridge region. In fact, the primary difference in ground-water conditions between the Piedmont and Blue Ridge region and the Northeast and Superior Uplands region is related to the materials that overlie the bedrock. In the Piedmont and Blue Ridge, these consist of unconsolidated material derived from weathering of the underlying bedrock. In the Northeast and Superior Uplands the overlying materials consist of glacial deposits which, having been transported either by ice or by streams, do not have a composition and structure controlled by that of the underlying bedrock. These differences in origin of the regolith between the Northeast and Superior Uplands and the Piedmont and Blue Ridge are an important consideration in the development of water supplies, as is discussed in the following paragraphs.

Recharge from precipitation generally begins in the fall after plant growth stops. It continues intermittently over the winter during thaws and culminates during the period between the spring thaw and the start of the growing season. Precipitation on the Northeast Upland, about 1,200 mm per year, is twice that on the Superior Upland, with the result that recharge, both to the glacial deposits and to the underlying bedrock, is largest in the Northeast. The glacial deposits in the region serve as a storage reservoir for the fractures in the underlying bedrock, in the same way the saprolite functions in the Piedmont and Blue Ridge region. The major difference is that the glacial deposits on hills and other upland areas are much thinner than the saprolite in similar areas in the Piedmont and Blue Ridge and, therefore, have a much smaller ground-water storage capacity.

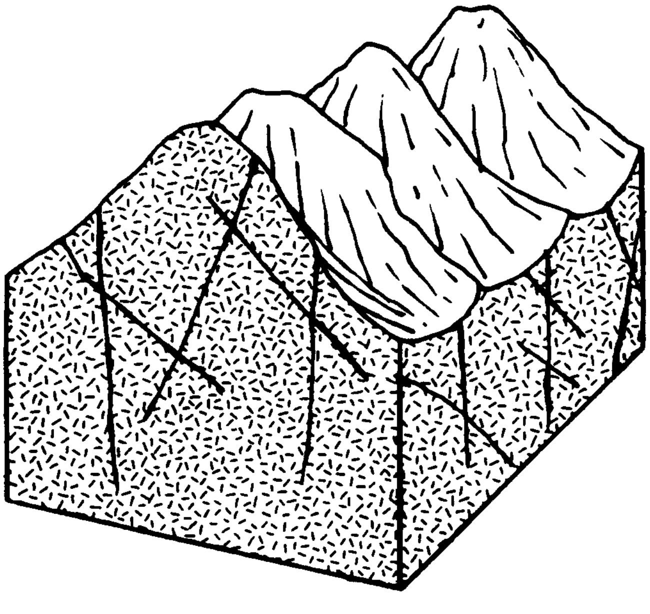
Water supplies in the Northeast and Superior Uplands region are obtained from open-hole drilled wells in bedrock, from drilled and screened or open-end wells in sand and gravel, and from large-diameter bored or dug wells in till. The development of water supplies from bedrock, especially in the Superior Upland, is more uncertain than from the fractured rocks in the Piedmont and Blue Ridge region because the ice sheets that advanced across the region removed the upper, more fractured part of the rock and also tended to obscure many of the fracture-caused depressions in the rock surface with the layer of glacial till. Thus, use of surface depressions in this region to select sites of bedrock wells is not as satisfactory as in the Piedmont and Blue Ridge.

Most of the rocks that underlie the Northeast and Superior Uplands are relatively insoluble, and, consequently, the ground water in both the glacial deposits and the bedrock generally contains less than 500 mg/l of dissolved solids. Two of the most significant water-quality problems confronting the region, especially the Northeast Upland section, are acid precipitation and pollution caused by salts used to de-ice highways. Much of the precipitation now falling on the Northeast (in 1982) has a pH in the range of 4 to 6 units. Because of the low buffering capacity of the soils derived from the rocks underlying the area, there is relatively little opportunity for the pH to be increased. One of the results of this is the gradual elimination of living organisms from many lakes and streams. The effect on ground-water quality, which will develop much more slowly, has not yet been determined. The second problem—that of de-icing salts—affects ground-water quality adjacent to streets and roads maintained for winter travel.

Northeast and Superior Uplands

(9A) Mountain Slopes

This hydrogeologic setting is characterized by steep slopes on the side of mountains, a thin soil cover and fractured bedrock. Ground water is obtained primarily from the fractures in the bedrock which may be of sedimentary, metamorphic, or igneous origin but which is commonly metamorphic or igneous. The fractures provide localized sources of ground water, and well yields are typically limited. Although precipitation is abundant, due to the steep slopes, thin soil cover and small storage capacity of the fractures, runoff is significant and ground-water recharge is moderate. Water levels are extremely variable but are commonly deep.



Setting 9 A Mountain Slopes

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	2-4	4	3	12
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	2	10	20
Topography	18+	1	1	1
Impact Vadose Zone	Metamorphic/ Igneous	5	4	20
Hydraulic Conductivity	1-100	3	1	3
		DRASTIC Index		75

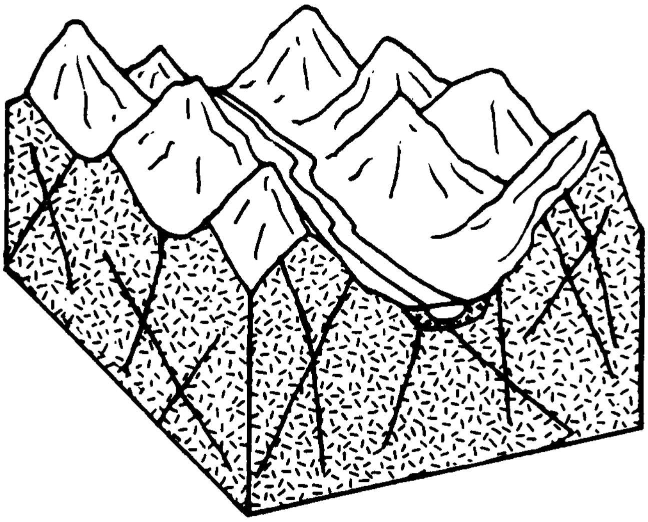
Setting 9 A Mountain Slopes

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	2-4	4	3	12
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Thin or Absent	5	10	50
Topography	18+	3	1	3
Impact Vadose Zone	Metamorphic/ Igneous	4	4	16
Hydraulic Conductivity	1-100	2	1	2
		Agricultural DRASTIC Index		102

Northeast and Superior Uplands

(9B) Alluvial Mountain Valleys

This hydrogeologic setting is characterized by thin, bouldery alluvium which overlies fractured bedrock of sedimentary, metamorphic, or igneous origin but which are commonly alternating sedimentary layers. The alluvium, which is derived from the surrounding slopes serves as a localized source of water. Water is obtained from sand and gravel layers which are interspersed between fine-grained deposits. Surficial deposits have typically weathered to a sandy loam. Water levels are relatively shallow but may be extremely variable. Ground water may also be obtained from the fractures in the underlying bedrock which are usually in direct hydraulic connection with the overlying alluvium.



Setting 9 B Alluvial Mountain Valleys

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	700-1000	3	6	18
		DRASTIC Index		180

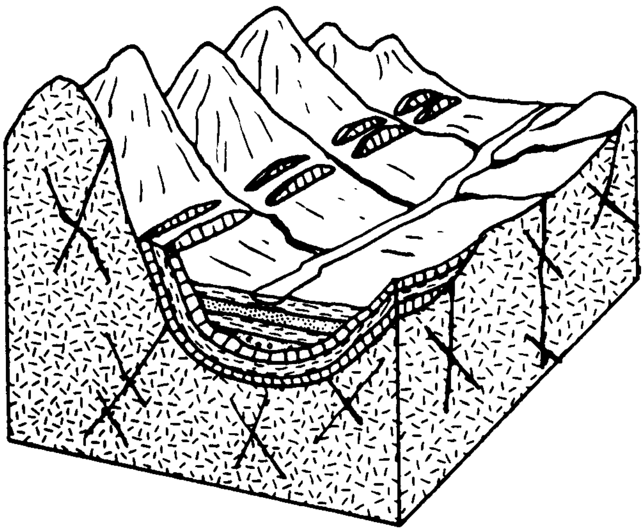
Setting 9 B Alluvial Mountain Valleys

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	700-1000	2	6	12
		Agricultural DRASTIC Index		202

Northeast and Superior Uplands

(9C) Mountain Flanks

This hydrogeologic setting is characterized by moderate topographic relief and moderately dipping, fractured, consolidated sedimentary rocks. Soil cover is usually thicker than on the mountain slopes and typically has weathered to a sandy loam. Although precipitation can be significant, ground-water recharge is moderate due to the slope. Water levels are typically moderately deep, although they are extremely variable. The mountain flanks serve as the recharge area for aquifers which are confined in adjacent lowland areas. Ground water is obtained from the permeable sedimentary rocks or from fractures and bedding planes in the sedimentary rocks. The sedimentary rocks may be underlain by fractured bedrock of igneous, metamorphic, or sedimentary origin which yield little water.



Setting 9 C Mountain Flanks

Feature	Range	General Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	2-4	4	3	12
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	2	6	12
Topography	12-18%	1	3	3
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	100-300	3	2	6

DRASTIC Index 106

Setting 9 C Mountain Flanks

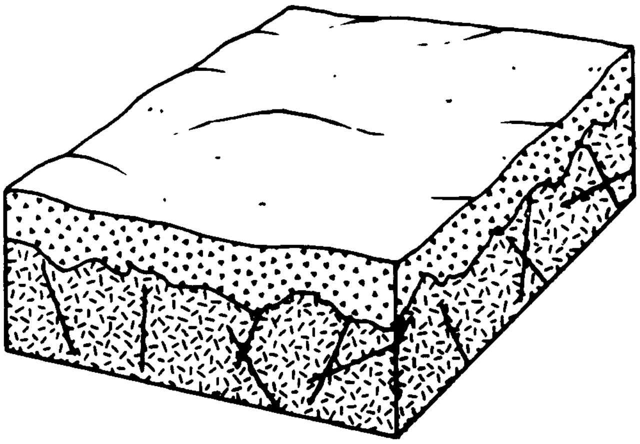
Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	2-4	4	3	12
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Sandy Loam	5	6	30
Topography	12-18%	3	3	9
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	100-300	2	2	4

Agricultural
DRASTIC Index 122

Northeast and Superior Uplands

(9Da) Glacial Till Over Crystalline Bedrock

This hydrogeologic setting is characterized by moderately low topographic relief and varying thicknesses of glacial till overlying severely fractured, folded, and faulted bedrock of igneous and metamorphic origin with minor occurrences of bedded sedimentary rocks. The till is chiefly unsorted deposits which may be interbedded with localized deposits of sand and gravel. Although ground water occurs in both the glacial deposits and fractured bedrock, the bedrock is the principal aquifer. The glacial till serves as a recharge source. Although precipitation is abundant, recharge is only moderately high because of the low permeability of the glacial till and the surficial deposits which typically weather to loam. Depth to water is extremely variable depending in part on the thickness of the glacial till, but is typically moderately shallow.



Setting 9 Da Glacial Till Over Crystalline Bedrock

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Loam	2	5	10
Topography	2-6%	1	9	9
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	1-100	3	1	3

DRASTIC Index 103

Setting 9 Da Glacial Till Over Crystalline Bedrock

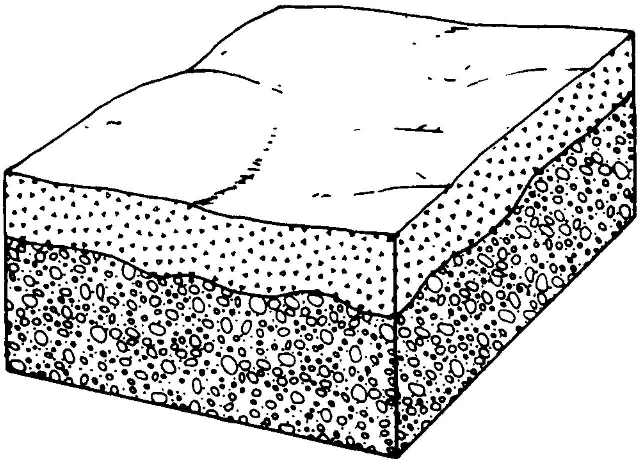
		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Metamorphic/ Igneous	3	3	9
Soil Media	Loam	5	5	25
Topography	2-6%	3	9	27
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	1-100	2	1	2

Agricultural
DRASTIC Index 134

Northeast and Superior Uplands

(9Db) Glacial Till Over Outwash

This hydrogeologic setting is characterized by low topography and outwash materials which are covered by varying thicknesses of glacial till. The till is chiefly unsorted deposits which may be interbedded with localized deposits of sand and gravel. Surficial deposits have usually weathered to a loam. Although ground water occurs in both the glacial till and in the underlying outwash, the outwash serves as the principal aquifer because the fine-grained deposits have been removed by glacial meltwater. The outwash is in direct hydraulic connection with the glacial till and the glacial till serves as a source of recharge for the underlying outwash. Precipitation is abundant in the region but recharge is moderate because of the relatively low permeability of the overlying glacial till. Depth to water table is extremely variable depending in part on the thickness of the glacial till, but averages around 30 feet.



Setting 9 Db Glacial Till Over Outwash

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Loam	2	5	10
Topography	2-6%	1	9	9
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	1000-2000	3	8	24

DRASTIC Index 129

Setting 9 Db Glacial Till Over Outwash

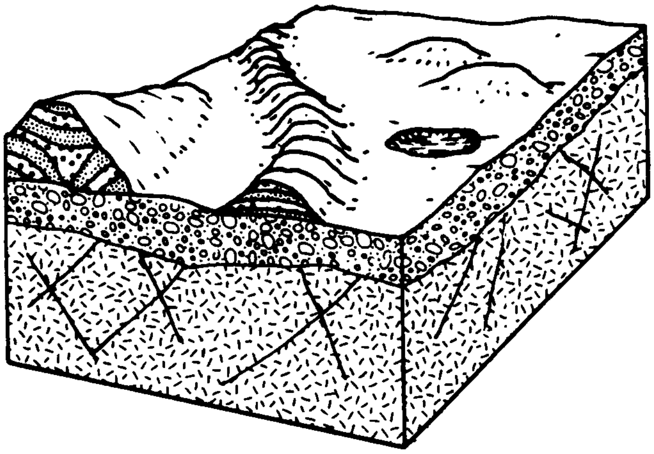
		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	30-50	5	5	25
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Loam	5	5	25
Topography	2-6%	3	9	27
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	1000-2000	2	8	16

Agricultural
DRASTIC Index 153

Northeast and Superior Uplands

(9E) Outwash

This hydrogeologic setting is characterized by moderate topographic relief and varying thickness of outwash which overlie fractured bedrock of sedimentary, metamorphic, or igneous origin. The outwash consists of water-washed deposits of sand and gravel which often serve as the principal aquifers in the area, and which typically have a sandy loam surficial layer. The outwash also serves as a source of recharge to the underlying bedrock. Recharge is abundant and ground-water recharge is high. Water levels are extremely variable, but are relatively shallow.



Setting 9 E Outwash

Feature	Range	General Weight	General Rating	General Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	1000-2000	3	8	24

DRASTIC Index 190

Setting 9 E Outwash

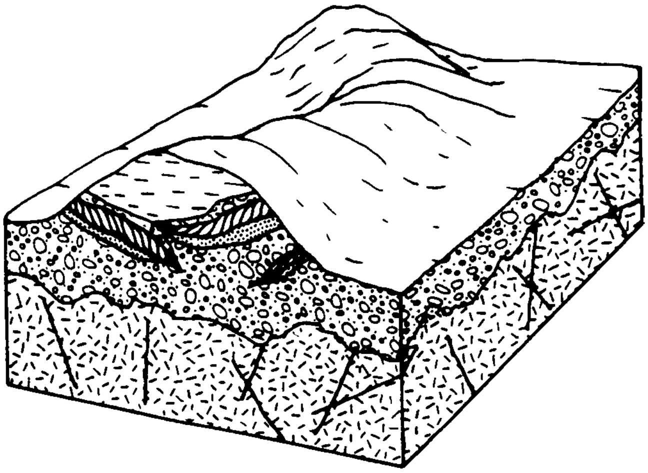
Feature	Range	Agricultural Weight	Agricultural Rating	Agricultural Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	1000-2000	2	8	16

Agricultural DRASTIC Index 210

Northeast and Superior Uplands

(9F) Moraine

This hydrogeologic setting is characterized by moderate topography and varying thicknesses of mixed glacial deposits which overlie fractured bedrock of sedimentary, igneous, or metamorphic origin. This setting is similar to (9E) Outwash in that the sand and gravel within the morainal deposits is well-sorted and serves as the principal aquifer in the area. These deposits also serve as a source of recharge for the underlying bedrock. Moraines also contain sediments that are typically unsorted and unstratified; these deposits contain more fines than outwash deposits, are less permeable and characteristically more like glacial till. Moraines are typically mounds or ridges of till which were deposited along the margin of a stagnant or retreating glacier. Surficial deposits often weather to a sandy loam. Precipitation is abundant throughout the region and ground-water recharge is moderately high. Water levels are extremely variable, based in part on the thickness of the glacial till, but are typically fairly shallow.



Setting 9 F Moraine

Feature	Range	General Weight	General Rating	General Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	6-12%	1	5	5
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	700-1000	3	6	18

DRASTIC Index 166

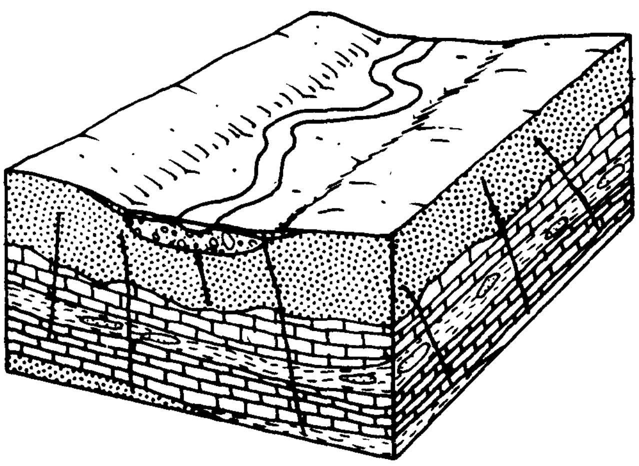
Setting 9 F Moraine

Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	6-12%	3	5	15
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	700-1000	2	6	12
		Agricultural DRASTIC Index		180

Northeast and Superior Uplands

(9Ga) River Alluvium With Overbank

This hydrogeologic setting is characterized by low topography and thin to moderately thick deposits of alluvium along parts of river valleys. The alluvium is underlain by fractured bedrock of sedimentary, metamorphic, or igneous origin. Water is obtained from sand and gravel layers which are interbedded with finer-grained alluvial deposits. The flood plain is covered by varying thicknesses of fine-grained silt and clay, called overbank deposits. The overbank thickness is usually greater along major streams (as much as 40 feet) and thinner along minor streams. Precipitation is abundant, but recharge is somewhat reduced because of the silty overbank deposits and subsequent clayey loam soils which typically cover the surface. Water levels are typically moderately shallow and may be hydraulically connected to the stream or river. The alluvium may serve as a significant source of water and is also usually in direct hydraulic connection with the underlying bedrock.



Setting 9 Ga River Alluvium With Overbank

Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Clay Loam	2	3	6
Topography	0-2%	1	10	10
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	1000-2000	3	8	24
		DRASTIC Index		136

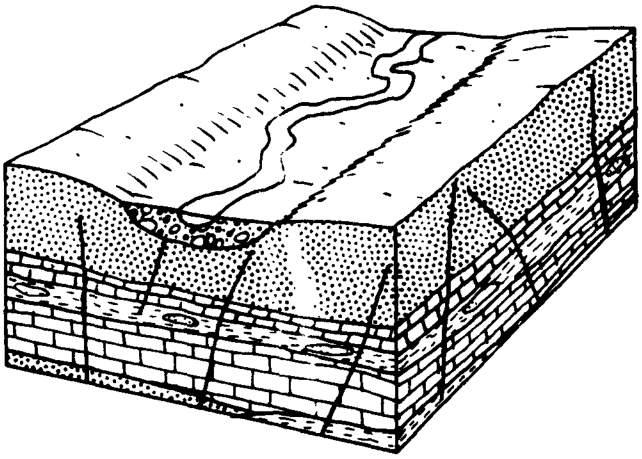
Setting 9 Ga River Alluvium With Overbank

Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Clay Loam	5	3	15
Topography	0-2%	3	10	30
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	1000-2000	2	8	16
		Agricultural DRASTIC Index		156

Northeast and Superior Uplands

(9Gb) River Alluvium Without Overbank

This hydrogeologic setting is identical to (9Ga) River Alluvium With Overbank except that no significant fine-grained flood plain deposits occupy the stream valley. This results in significantly higher recharge where precipitation is adequate and sandy soils occur at the surface. Water levels are moderate to shallow in depth. Hydraulic contact with the surface stream is usually excellent, with alternating recharge/discharge relationships varying with stream stage. These deposits serve as a good source of recharge to the underlying fractured bedrock.



Setting 9 Gb River Alluvium Without Overbank

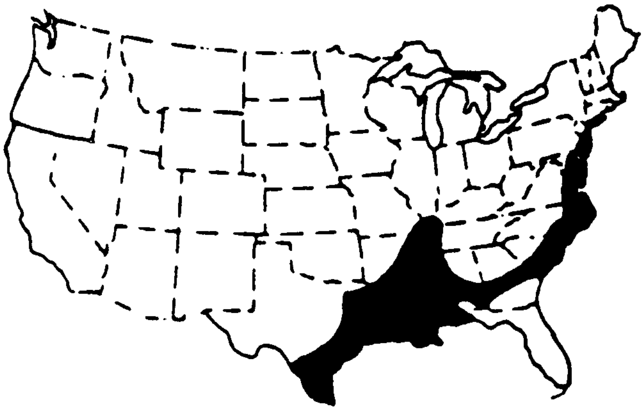
Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	0-2%	1	10	10
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	1000-2000	3	8	24
		DRASTIC Index		191

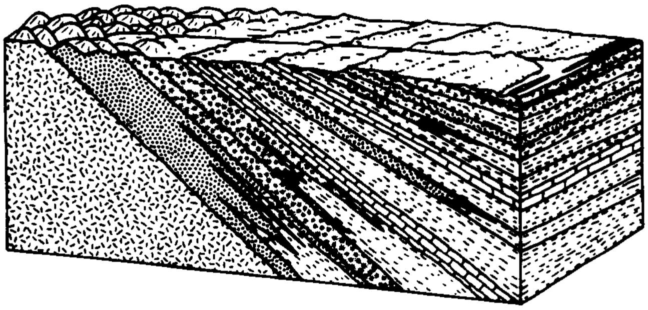
Setting 9 Gb River Alluvium Without Overbank

Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	0-2%	3	10	30
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	1000-2000	2	8	16
		Agricultural DRASTIC Index		213

10. Atlantic and Gulf Coastal Plain

(Complexly interbedded sand, silt, and clay)





The Atlantic and Gulf Coastal Plain region is an area of about 844,000 km^2 extending from Cape Cod, Massachusetts, on the north to the Rio Grande in Texas on the south. This region does not include Florida and parts of the adjacent States; although those areas are a part of the Atlantic and Gulf Coastal Plain physiographic province, they together form a separate ground-water region. (See region 11, "Southeast Coastal Plain.")

The Atlantic and Gulf Coastal Plain region ranges in width from a few kilometers near its northern end to nearly a thousand kilometers in the vicinity of the Mississippi River. The great width near the Mississippi reflects the effect of a major downwarped zone in the Earth's crust that extends from the Gulf of Mexico to about the confluence of the Mississippi and Ohio Rivers. This area is referred to as the Mississippi embayment.

The topography of the region ranges from extensive, flat, coastal swamps and marshes 1 to 2 m above sea level to rolling uplands, 100 to 250 m above sea level, along the inner margin of the region.

The region is underlain by unconsolidated sediments that consist principally of sand, silt, and clay transported by streams from the adjoining uplands. These sediments, which range in age from Jurassic to the present, range in thickness from less than a meter near the inner edge of the region to more than 12,000 m in southern Louisiana. The greatest thicknesses are along the seaward edge of the region and along the axis of the Mississippi embayment. The sediments were deposited on floodplains and as deltas where streams reached the coast and, during different invasions of the region by the sea, were reworked by waves and ocean currents. Thus, the sediments are complexly interbedded to the extent that most of the named geologic units into which they have been divided contain layers of the different types of sediment that underlie the region. These named geologic units (or formations) dip toward the coast or toward the axis of the Mississippi embayment, with the result that those that crop out at the surface form a series of bands roughly parallel to the coast or to the axis of the embayment. The oldest formations crop out along the inner margin of the region, and the youngest crop out in the coastal area.

Within any formation the coarsest grained materials (sand, at places interbedded with thin gravel layers) tend to be most abundant near source areas. Clay and silt layers become thicker and more numerous downdip.

Although sand, silt, and clay, as noted above, are the principal types of material underlying the Atlantic and Gulf Coastal Plain, there are also a small amount of gravel interbedded with the sand, a few beds composed of mollusk shells, and a small amount of limestone present in the region. The most important limestone is the semi-consolidated Castle Hayne Limestone of Eocene age which underlies an area of about 26,000 km^2 in eastern North Carolina, is more than 200 m thick in much of the area, and is the most productive aquifer in North Carolina. A soft, clayey limestone (the chalk of the Selma Group) of Late

Cretaceous age underlies parts of eastern Mississippi and western Alabama, but instead of being an aquifer it is an important confining bed.

From the standpoint of well yields and ground-water use, the Atlantic and Gulf Coastal Plain is one of the most important regions in the country. Recharge to the ground-water system occurs in the interstream areas, both where sand layers crop out and by percolation downward across the interbedded clay and silt layers. Discharge from the system occurs by seepage to streams, estuaries, and the ocean. Movement of water from recharge areas to discharge areas is controlled, as in all ground-water systems, by hydraulic gradients, but in this region the pattern of movement is complicated by down-dip thickening of clay which hampers upward discharge. As a result, movement down the dip of the permeable layers becomes increasingly slow with increasing distance from the outcrop areas. This causes many flow lines to converge on the discharge areas located on major streams near the downdip part of outcrop areas. These areas of concentrated ground-water discharge are referred to as "artesian-water gaps" by LeGrand and Pettyjohn (1981).

Wells that yield moderate to large quantities of water can be constructed almost anywhere in the region. Because most of the aquifers consist of unconsolidated sand, wells require screens; where the sand is fine-grained and well sorted, the common practice is to surround the screens with a coarse sand or gravel envelope.

Withdrawals near the outcrop areas of aquifers are rather quickly balanced by increases in recharge and (or) reductions in natural discharge. Withdrawals at significant distances downdip do not appreciably affect conditions in the outcrop area and thus must be partly or largely supplied from water in storage in the aquifers and confining beds.

The reduction of storage in an aquifer in the vicinity of a pumping well is reflected in a decline in ground-water levels and is necessary in order to establish a hydraulic gradient toward the well. If withdrawals are continued for long periods in areas underlain by thick sequences of unconsolidated deposits, such as the Atlantic and Gulf Coastal Plain, the lowered ground-water levels in the aquifer may result in drainage of water from layers of silt and clay. The depletion of storage in fine-grained beds results in subsidence of the land surface. Subsidence in parts of the Houston area totaled about 9 m as of 1978. Subsidence near pumping centers in the Atlantic Coastal Plain has not yet been confirmed but is believed to be occurring, though at a slower rate than along the Texas Gulf Coast.

The depletion of storage in confining beds is permanent, and subsidence of the land surface that results from such depletion is also permanent. On the other hand, depletion of storage in aquifers may not be fully permanent, depending on the availability of recharge. In arid and semiarid regions, recharge rates are extremely small, and depletion of aquifer storage is, for practical purposes, permanent. Depletion of storage in aquifers in these regions is referred to as mining. In humid regions, recharge is sufficient to replace aquifer storage rather quickly, once withdrawals are stopped, so that depletion of aquifer storage in these areas is not considered to be mining. The important point is that depletion of storage in the confining layers of silt and clay in both arid and humid regions is permanent but is not normally considered to be ground-water mining. The term "mining" is applied by most ground-water hydrologists only to areas in which aquifer storage is being permanently depleted.

Depletion of storage in the aquifers underlying large areas of the Atlantic and Gulf Coastal Plain is reflected in long-term declines in ground-water levels. These declines suggest that withdrawals in these areas are exceeding the long-term yield of the aquifers.

This is a water-management problem that will become more important as rates of withdrawal and the lowering of water levels increase. Solutions to this problem include (1) concentrating withdrawals as close as possible to outcrop (recharge) areas, (2) dispersing withdrawals in regions remote from the outcrop areas over the widest possible area, and (3) increasing withdrawals from surficial aquifers to the maximum possible extent.

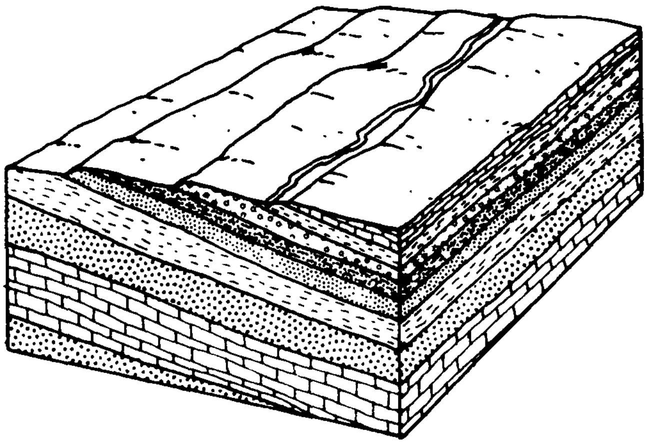
Another problem that affects ground-water development in the region concerns the presence of saline water in the deeper parts of most aquifers. The occurrence of saline water is controlled by the circulation of freshwater which, as noted previously, becomes increasingly slow down the dip of the aquifers. Thus, in some of the deeper aquifers, the interface between freshwater and saltwater is inshore, but in parts of the region, including parts of Long Island, New Jersey, and Mississippi, the interface in the most intensively developed aquifers is a significant distance offshore. Pumping near the interfaces has resulted in problems of saltwater encroachment locally.

Another significant feature of the ground-water system in this region is the presence of "geopressured" zones at depths of 1,800 to 6,100 m in Texas and Louisiana which contain water at a temperature of 80°C to more than 273°C. Water in these zones contains significant concentrations of natural gas, and the water in some zones is under pressures sufficient to support a column of water more than 4,000 m above land surface. Because the elevated temperature, natural gas, and high pressures are all potential energy sources, these zones are under intensive investigation.

Atlantic and Gulf Coastal Plain

(10Aa) Confined Regional Aquifers

This hydrogeologic setting is characterized by moderately low topographic relief and gently dipping, complexly interbedded unconsolidated and semi-consolidated deposits which consist primarily of sand, silt, and clay. Outcrops of these deposits form a series of bands roughly parallel to the coast or to the axis of the Mississippi Embayment. The outcrop areas and overlying semi-permeable beds are the principal sources of recharge to the formations which serve as regional aquifers. Precipitation is abundant and recharge is moderately high in the outcrop areas but low regionally to deep zones. Surficial deposits typically weather to a sandy loam. Large quantities of water are obtained from the sand and gravel and sand deposits within the aquifer. Water levels are extremely variable and typically are shallower toward the shoreline. When ground water is heavily pumped near the shoreline, these aquifers are very susceptible to salt-water intrusion. Since the shallow aquifers are very vulnerable to pollution due to their permeable nature, and the deeper aquifers are recharged from the shallow ones, the entire system is somewhat susceptible to ground-water pollution. The degree of vulnerability varies according to the nature of the deposits and the amount of recharge.



Setting 10 Aa Confined Regional Aquifers

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	100+	5	1	5
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	*	2	1	2
Topography	*	1	1	1
Impact Vadose Zone	Silt and Clay	5	1	5
Hydraulic Conductivity	300-700	3	4	12
		DRASTIC Index		53

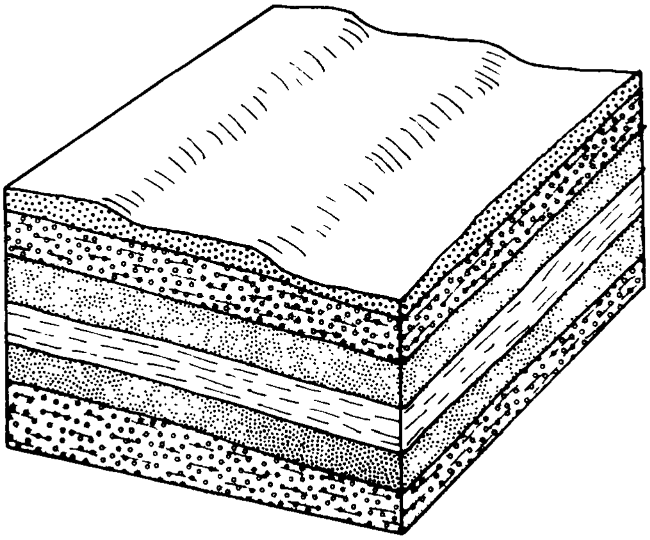
Setting 10 Aa Confined Regional Aquifers

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	100+	5	1	5
Net Recharge	0-2	4	1	4
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	*	5	1	5
Topography	*	3	1	3
Impact Vadose Zone	Silt and Clay	4	1	4
Hydraulic Conductivity	300-700	2	4	8
		Agricultural DRASTIC Index		53

Atlantic and Gulf Coastal Plain

(10Ab) Unconsolidated & Semi-Consolidated Shallow Surficial Aquifer

This setting is very similar to (10Aa) Confined Regional Aquifers except that the principal aquifer is the shallow surficial deposits which serve as a local source of water and typically provide recharge for the regional aquifer. Water is obtained from the surficial sand and gravel which may be separated from the underlying regional aquifer by a confining layer. This confining layer typically leaks providing recharge to the deeper zones. Surficial deposits are sandy loams. Water levels tend to be quite shallow, especially near the coast. Precipitation is abundant and recharge to the ground water is high. These deposits are very vulnerable to ground-water pollution due to their permeable nature.



Setting 10 Ab Unconsolidated & Semi-Consolidated Shallow Surficial Aquifer

Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	700-1000	3	6	18

DRASTIC Index 184

Setting 10 Ab Unconsolidated & Semi-Consolidated Shallow Surficial Aquifer

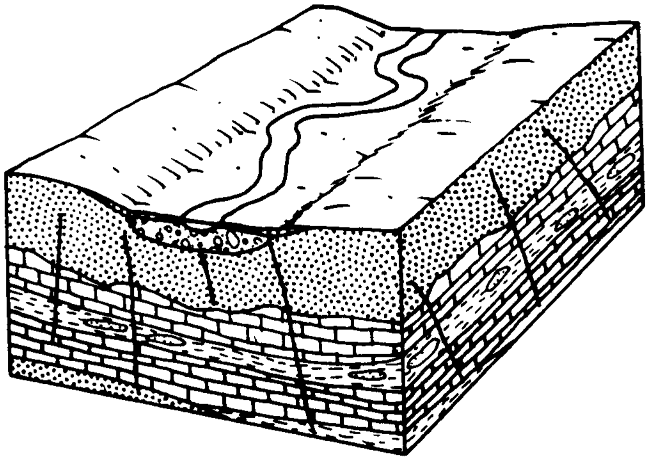
Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	700-1000	2	6	12

Agricultural
DRASTIC Index 206

Atlantic and Gulf Coastal Plain

(10Ba) River Alluvium With Overbank

This hydrogeologic setting is characterized by low topography and thin to moderately thick deposits of alluvium along parts of river valleys. The alluvium is underlain by consolidated and semi-consolidated sedimentary rocks. Water is obtained from sand and gravel layers which are interbedded with finer-grained alluvial deposits. The floodplain is covered by varying thicknesses of fine-grained, silty deposits called overbank deposits. The overbank thickness is usually greater along major streams (as much as 40 feet) and thinner along minor streams. Precipitation in the region is abundant, but recharge is somewhat reduced because of the silty overbank deposits and subsequent silty soils which typically cover the surface. Water levels are typically moderately shallow. The alluvium may serve as a significant source of water and may be in direct hydraulic connection with the underlying sedimentary rocks. The alluvium may also serve as a source of recharge to the underlying bedrock. Many streams in this setting provide only fine-grained deposits (silts and clays) and as such do not form good aquifers. They still, however, provide a good source of recharge.



Setting 10 Ba River Alluvium With Overbank Deposit

Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Silty Loam	2	4	8
Topography	0-2%	1	10	10
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	700-1000	3	6	18

DRASTIC Index 132

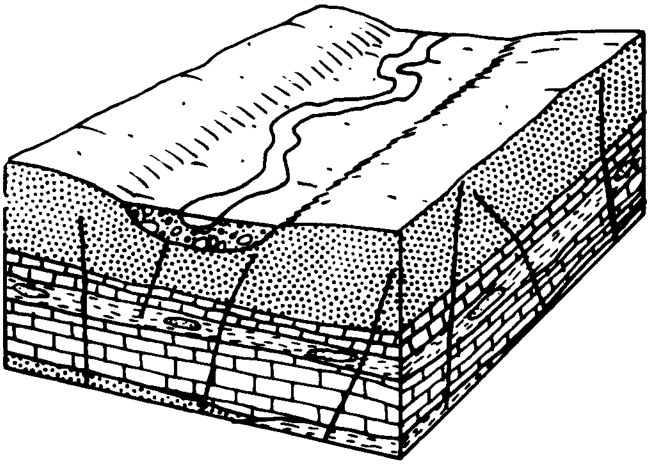
Setting 10 Ba River Alluvium With Overbank Deposit

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	7-10	4	8	32
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Silty Loam	5	4	20
Topography	0-2%	3	10	30
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	700-1000	2	6	12
		Agricultural DRASTIC Index		157

Atlantic and Gulf Coastal Plain

(10Bb) River Alluvium Without Overbank

This setting is identical to (10Ba) River Alluvium With Overbank except that no significant fine-grained floodplain deposits occupy the stream valley. This results in significantly higher recharge and sandy soils at the surface. Water levels are typically closer to the surface because banks of fine-grained deposits are not present. Throughout much of this region there is an abundance of coarse-grained material, which limits this setting for water supply. These materials, however, provide a good source of recharge to the underlying consolidated and semi-consolidated bedrock.



Setting 10 Bb River Alluvium Without Overbank Deposit

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	0-2%	1	10	10
Impact Vadose Zone	S & G w/sig. Silt and Clay	5	6	30
Hydraulic Conductivity	1000-2000	3	8	24
		DRASTIC Index		187

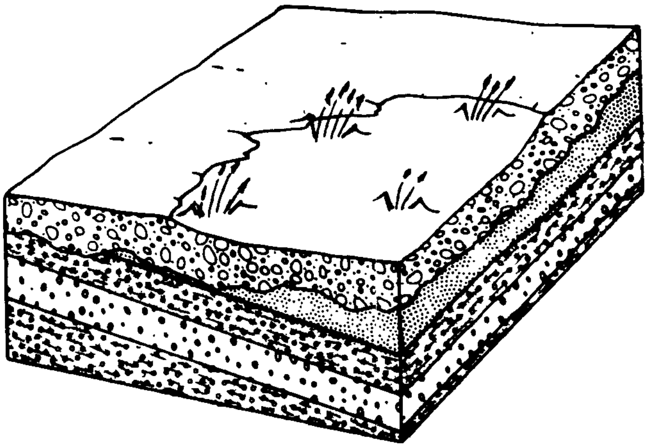
Setting 10 Bb River Alluvium Without Overbank Deposit

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	0-2%	3	10	30
Impact Vadose Zone	S & G w/sig. Silt and Clay	4	6	24
Hydraulic Conductivity	1000-2000	2	8	16
		Agricultural DRASTIC Index		220

Atlantic and Gulf Coastal Plain

(10C) Swamp

This hydrogeologic setting is characterized by low topographic relief and deposits of sand, and sand and gravel, which overlie consolidated and semi-consolidated sedimentary rocks. Surficial deposits are typically sand mixed with organic material. The surficial sands are usually in hydraulic connection with the underlying aquifers and serve as a source of recharge. Precipitation is abundant and potential recharge is high. Water levels are typically at or near the surface during the majority of the year. While a swamp is frequently a ground water discharge zone, and as such not especially vulnerable to pollution, it is surficially an environmentally sensitive area. It should also be noted that a slight reversal in gradient would easily convert the swamp into a ground water recharge zone. Thus, it is potentially highly vulnerable to ground-water pollution.



Setting 10 C Swamp

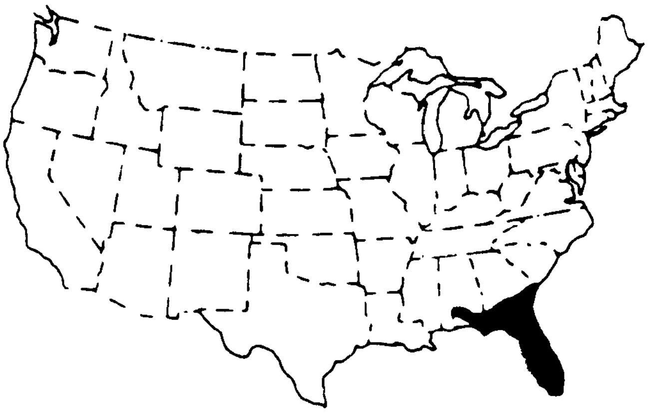
Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	0-5	5	10	50
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	0-2%	1	10	10
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	1000-2000	3	8	24
		DRASTIC Index		202

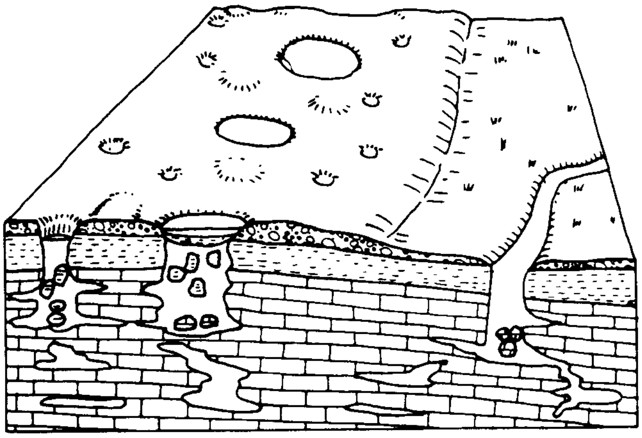
Setting 10 C Swamp

Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	0-5	5	10	50
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	0-2%	3	10	30
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	1000-2000	2	8	16
		Agricultural DRASTIC Index		233

11. Southeast Coastal Plain

(Thick layers of sand and clay over semi-consolidated carbonate rocks)





The Southeast Coastal Plain is an area of about 212,000 km² in Alabama, Florida, Georgia, and South Carolina. It is a relatively flat, low-lying area in which altitudes range from sea level at the coast to about 100 m down the center of the Florida peninsula and as much as 200 m on hills in Georgia near the interior boundary of the region. Much of the area, including the Everglades in southern Florida, is a nearly flat plain less than 10 m above sea level.

The land surface of the Southeast Coastal Plain is underlain by unconsolidated deposits of Pleistocene age consisting of sand, gravel, clay, and shell beds and, in southeastern Florida, by semi-consolidated limestone. From the coast up to altitudes of nearly 100 m, the surficial deposits are associated with marine terraces formed when the Coastal Plain was inundated at different times by the sea. In most of the region the surficial deposits rest on formations, primarily of middle to late Miocene age, composed of interbedded clay, sand, and limestone. The most extensive Miocene deposit is the Hawthorn Formation. The formations of middle to late Miocene age, and where those formations are absent, the surficial deposits overlie semi-consolidated limestones and dolomites that are as much as 1,500 m thick. These carbonate rocks range in age from early Miocene to Paleocene and are generally referred to collectively as Tertiary limestones.

The Tertiary limestone that underlies the Southeast Coastal Plain constitutes one of the most productive aquifers in the United States and is the feature that justifies treatment of the region separately from the remainder of the Atlantic and Gulf Coastal Plain. The aquifer, which is known as the Floridan aquifer, underlies all of Florida and southeast Georgia and small areas in Alabama and South Carolina. The Floridan aquifer consists of layers several meters thick composed largely of loose aggregations of shells of foraminifers and fragments of echinoids and other marine organisms interbedded with much thinner layers of cemented and cherty limestone. The Floridan, one of the most productive aquifers in the world, is the principal source of ground-water supplies in the southeast Coastal Plain region.

In southern Florida, south of Lake Okeechobee, and in a belt about 30 km wide northward along the east coast of Florida to the vicinity of St. Augustine, the water in the Floridan aquifer contains more than 100 mg/l of chloride. In this area, most water supplies are obtained from surficial aquifers, the most notable of which underlies the southeastern part of Florida and which in the Miami area consists of 30 to 100 m of cavernous limestone and sand referred to as the Biscayne aquifer. The Biscayne is an unconfined aquifer which is recharged by local precipitation and by infiltration of water from canals that drain water from impoundments (conservation areas) developed in the Everglades. It is the principal source of water for municipal, industrial, and irrigation uses and can yield as much as 5 m^3 min^{-1} (1,300 gal min^{-1}) to small-diameter wells less than 25 m deep finished with open holes only 1 to 2 m in length.

The surficial aquifers in the remainder of the region are composed primarily of sand, except in the coastal zones of Florida where the sand is interbedded with shells and thin limestones. These surficial aquifers serve as sources of small ground-water supplies throughout the region and are the primary sources of ground water where the water in the Floridan aquifer contains more than about 259 mg/l of chloride.

The Floridan aquifer, as noted above, is the principal source of ground water in the region. Ground water in the upper part of the aquifer is unconfined in the principal recharge areas in Georgia and in west-central Florida. In the remainder of the region, water in the aquifer is confined by clay in the Hawthorn Formation and in other beds that overlie the aquifer. Recharge occurs where the potentiometric surface of the Floridan aquifer is lower than the water table in the overlying surficial aquifer. The principal recharge areas include a broad area along the west side of Florida extending from the central part of the peninsula to south-central Georgia and an area extending from west-central Florida through southeast Alabama into southwest Georgia. In these areas, recharge rates are estimated to exceed 120 mm yr^{-1} (5 in. yr^{-1}). Recharge occurs by infiltration of precipitation directly into the limestone, where it is exposed at the land surface, and by seepage through the permeable soils that partly mantle the limestone in the outcrop areas. Considerable recharge also occurs in the higher parts of the recharge areas through permeable openings in the confining beds, where these beds have been breached by the collapse of caverns in the limestone during the process of sinkhole formation. Thus, the land surface in most of Florida north of Lake Okeechobee is marked by thousands of closed depressions ranging in diameter from a few meters to several kilometers. The larger depressions, which represent a more advanced stage of solution of the limestone and collapse of the overlying material, are occupied by lakes generally referred to as sinkhole lakes.

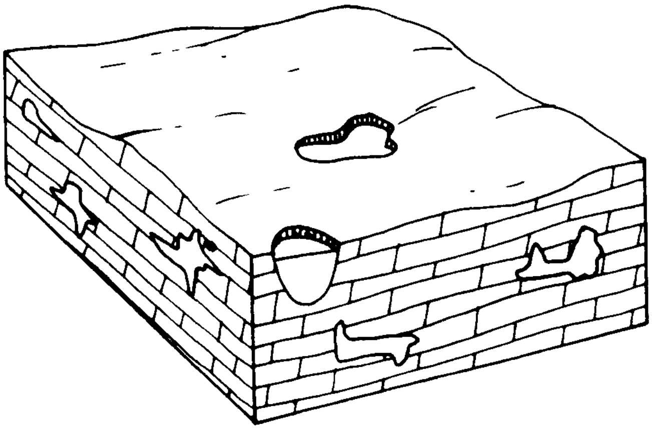
Discharge from the Floridan aquifer occurs through springs and by seepage to streams. Considerable discharge also occurs by diffuse seepage across the overlying confining beds in areas where the potentiometric surface of the aquifer stands at a higher altitude than the water table. In most of these areas, which include the southern third of the Florida peninsula, the east coast area and major stream valleys of Florida, and the coastal zone and major stream valleys of Georgia and South Carolina, wells open to the aquifer will flow at the land surface. Such wells are called "flowing artesian wells." The most spectacular discharge from the Floridan aquifer is through sinkholes exposed along streams and offshore. Florida has 27 springs of the first magnitude at which the average discharge exceeds 2.83 m^3 sec^{-1} (100 ft^3 sec^{-1}). The largest is Silver Springs, which has an average discharge of 23.2 m^3 sec^{-1} (530 million gallons per day) and reached a maximum discharge of 36.5 m^3 sec^{-1} on September 28, 1960. Heath and Conover (1981) estimate that the combined discharge from Florida's springs is 357 m^3 sec^{-1} (8 billion gallons per day).

The marked difference in ground-water conditions between the Southeast Coastal Plain and the Atlantic and Gulf Coastal Plain regions is apparent in the response of ground-water levels to withdrawals. In the Atlantic and Gulf Coastal Plain region most large withdrawals are accompanied by a pronounced continuing decline in ground-water levels. In the Southeast Coastal Plain, on the other hand, large withdrawals have significantly lowered ground-water levels in only a few areas.

Southeast Coastal Plain

(11A) Solution Limestone

This hydrogeologic setting is characterized by low to moderate topographic relief and deposits of limestone which have been partially dissolved to form a network of solution cavities and caves. Surficial deposits typically consist of sands. Precipitation is abundant and recharge is high. Water levels are variable but are usually moderate in the limestone and shallow in the overlying surficial sands. These sands serve as an important source of recharge for the limestones. Due to the presence of a shallow water table and direct recharge to the limestone these surficial sands are very vulnerable to pollution. Near the coast, these aquifers are very susceptible to salt-water intrusion.



Setting 11 A Solution Limestone

Feature	Range	General Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Karst Limestone	3	10	30
Soil Media	Sand	?	9	18
Topography	2-6%	1	9	9
Impact Vadose Zone	Karst Limestone	5	10	50
Hydraulic Conductivity	2000+	3	10	30

DRASTIC Index 218

Setting 11 A Solution Limestone

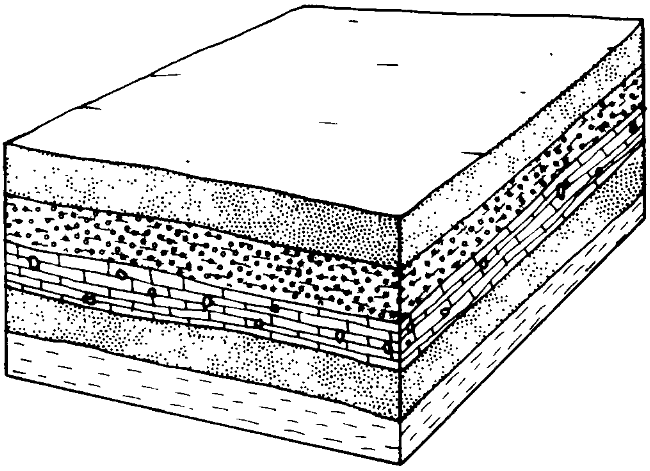
Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Karst Limestone	3	10	30
Soil Media	Sand	5	9	45
Topography	2-6%	3	9	27
Impact Vadose Zone	Karst Limestone	4	10	40
Hydraulic Conductivity	2000+	2	10	20

Agricultural DRASTIC Index 243

Southeast Coastal Plain

(11B) Coastal Deposits

This hydrogeologic setting is characterized by flat topography and unconsolidated deposits of carbonate, sand, gravel, clay, and shell beds which overlie semi-consolidated carbonate rocks. The surficial deposits serve as direct use sources of ground water and also serve as recharge for the underlying carbonate rocks where the gradient is downward toward the carbonates. The carbonates serve as a source of ground water but may contain saline water in some areas. Precipitation is abundant and recharge is high. Water levels may vary, but are typically close to the surface.



Setting 11 B Coastal Deposits

Feature	Range	General Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	0-2%	1	10	10
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	700-1000	3	6	18

DRASTIC Index 191

Setting 11 B Coastal Deposits

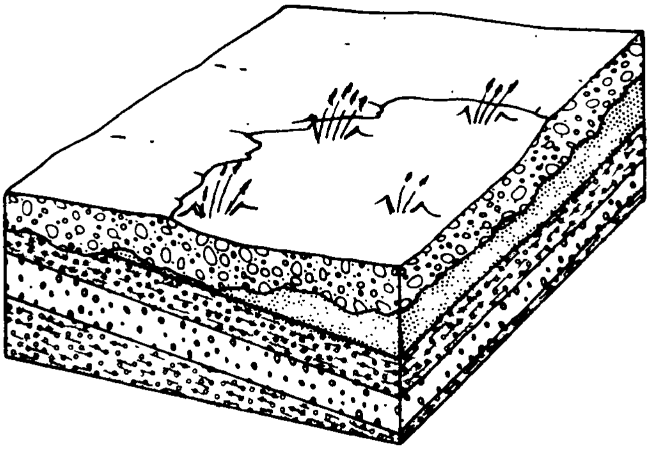
Feature	Range	Agricultural Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	0-2%	3	10	30
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	700-1000	2	6	12

Agricultural DRASTIC Index 224

Southeast Coastal Plain

(11C) Swamp

This hydrogeologic setting is characterized by flat topographic relief, very high water levels, and deposits of limestone which have partially been dissolved to form a network of solution cavities and caves. Soils are typically sand and recharge is high due to the abundant precipitation. The limestone typically serves as the major regional aquifer. Water levels are typically at or above the surface during the majority of the year. These swamps are typically discharge areas, but due to their environmental vulnerability, and possible gradient reversal, they should be regarded as areas of maximum (potential) recharge.



Setting 11 C Swamp

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	0-5	5	10	50
Net Recharge	10+	4	9	36
Aquifer Media	Karst Limestone	3	10	30
Soil Media	Sand	2	9	18
Topography	0-2%	1	10	10
Impact Vadose Zone	Karst Limestone	5	10	50
Hydraulic Conductivity	2000+	3	10	30

DRASTIC Index 224

Setting 11 C Swamp

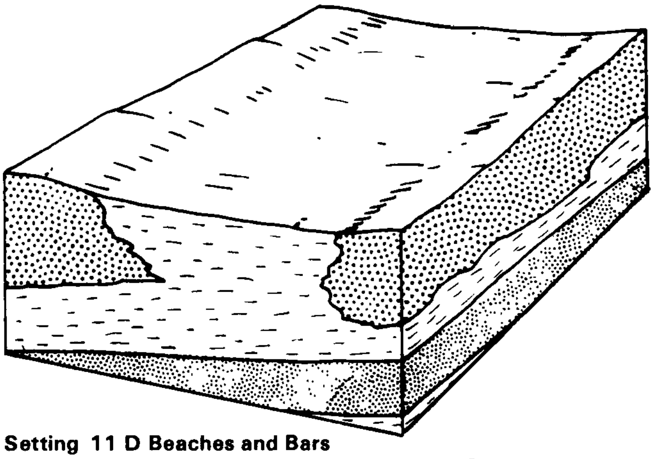
		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	0-5	5	10	50
Net Recharge	10+	4	9	36
Aquifer Media	Karst Limestone	3	10	30
Soil Media	Sand	5	9	45
Topography	0-2%	3	10	30
Impact Vadose Zone	Karst Limestone	4	10	40
Hydraulic Conductivity	2000+	2	10	20

Agricultural DRASTIC Index 251

Southeast Coastal Plain

(11D) Beaches and Bars

This hydrogeologic setting is characterized by moderate to flat topographic relief and unconsolidated deposits of water-washed sands. These sands are well-sorted and very permeable, and may serve as localized sources of ground water. These deposits also serve as a source of recharge to the underlying unconsolidated coastal deposits. Precipitation is abundant and recharge is high. Water levels may vary, but are typically shallow. These areas are highly susceptible to pollution due to their high permeabilities.



Setting 11 D Beaches and Bars

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	700-1000	3	6	18

DRASTIC Index 190

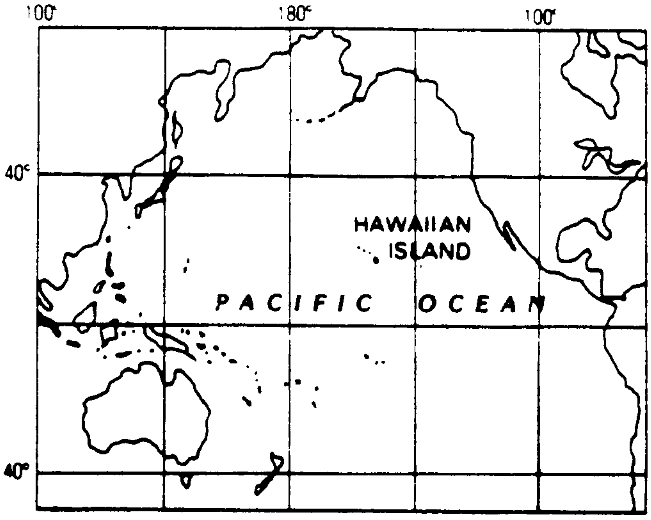
Setting 11 D Beaches and Bars

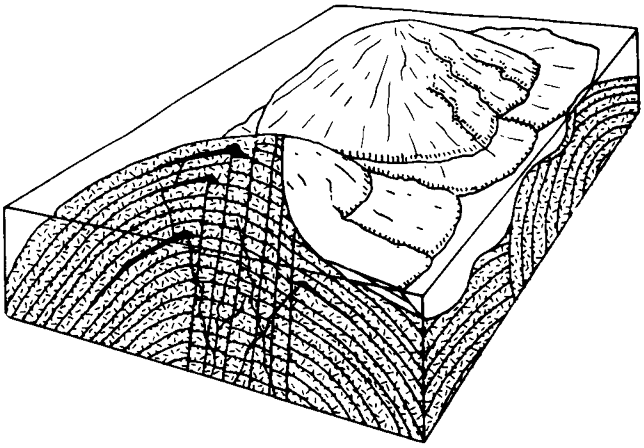
		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	36
Hydraulic Conductivity	700-1000	2	6	12

Agricultural DRASTIC Index 225

12. Hawaiian Islands

(Lava flows segmented in part by dikes, interbedded with ash deposits, and partly overlain by alluvium)





The Hawaiian Islands region encompasses the State of Hawaii and consists of eight major islands occupying an area of 16,707 km^2 in the Pacific Ocean 3,700 km southeast of California. The islands are the tops of volcanoes that rise from the ocean floor and stand at altitudes ranging from a few meters to more than 4,000 m above sea level. Each island was formed by lava that issued from one or more eruption centers. The islands have a hilly to mountainous appearance resulting from erosion that has carved valleys into the volcanoes and built relatively narrow plains along parts of the coastal areas.

Each of the Hawaiian Islands is underlain by hundreds of distinct and separate lava flows, most of which are composed of basalt. The lavas issued in repeated outpourings from narrow zones of fissures, first below sea level, then above it. The lavas that extruded below the sea are relatively impermeable. Those formed above sea level tend to be highly permeable, with interconnected openings that formed as the lava cooled, cavities and openings that were not filled by the overlying flow, and lava tubes (tunnels). The central parts of the thicker flows tend to be more massive and less permeable; the most common water-bearing openings are joints and faults that formed after the lava solidified. Thin layers of ash and weathered volcanic rock occur irregularly between some of the flows that formed above sea level. The lava flows in valleys and parts of the coastal plains are covered by a thin layer of alluvium consisting of coral (limestone) fragments, sand-size fragments of basalt, and clay.

The fissures through which the lava erupted tend to cluster near eruption centers. Flows from the fissures moved down depressions on the adjacent slopes to form layers of lava that dip at angles of 4 to 10 degrees toward the margins of the volcanoes. The result, prior to modification by erosion, is a broad, roughly circular, gently convex mountain similar in shape to a warrior's shield. Thus, volcanoes of the Hawaiian type are referred to as shield volcanoes. When eruption along a fissure ceases, the lava remaining in the fissure solidifies to form a dike.

All of the islands have sunk, to some extent, as a result of a downward flexing of the Earth's crust caused by the weight of the volcanoes. This has resulted in flows that formed above sea level being depressed below sea level. The upper parts of these flows contain freshwater that serves as an important source of water.

In mineral composition and nature of the water-bearing openings, the lavas that form the Hawaiian Islands are very similar to those in the Columbia Plateau region. Thus, from these two standpoints, these regions could be combined into one. There is, however, one important difference that justifies their treatment as separate regions. This difference relates to the presence of seawater around and beneath the islands, which significantly affects the occurrence and development of water supplies.

From the standpoint both of description and of development, it is useful to divide the ground-water system of the Hawaiian Islands into three parts. The first part consists of the higher areas of the islands in the vicinity of the eruption centers. The rocks in these areas are formed into a complex series of vertical compartments surrounded by dikes developed along eruption fissures. The ground water in these compartments is referred to as dike-impounded water. The second, and by far the more important, part of the system consists of the lava flows that flank the eruption centers and that contain fresh ground water floating on saline ground water. These flank flows are partially isolated hydraulically from the vertical compartments developed by the dikes that surround the eruption centers. The fresh ground water in these flows is referred to as basal ground water. In parts of the coastal areas the basal water is confined by the overlying alluvium. The third part of the system consists of fresh water perched, primarily in lava flows, on soils, ash, or thick impermeable lava flows above basal ground water.

The ground-water system is recharged by precipitation which ranges annually from about 160 mm to more than 11,000 mm. This wide range in precipitation reflects the effect of the islands on the moist northeast trade winds. As the moisture-laden winds are deflected upward by the mountains, precipitation falls on the higher elevations. Precipitation is heaviest on mountains below 1,000 m and lightest in the coastal areas on the leeward side of the islands and at elevations above 1,000 m on the islands of Maui and Hawaii. The average annual precipitation on the islands is estimated to be about 1,800 mm. Because of the highly permeable nature of the volcanic soils, it is estimated that about 30 percent of the precipitation recharges the ground-water system.

Some discharge of dike-impounded ground water doubtless occurs through fractures in the dikes into the flanking lava flows. This movement must be small, however, because water stands in the compartments at levels hundreds of meters above sea level and the principal discharge occurs as springs on the sides and at the heads of valleys where erosion has removed parts of the dikes. Both the basal ground water and the perched ground water in the lava flows surrounding the dike-bounded compartments is recharged by precipitation and by streams leaving the dike-bounded area. Discharge is to streams and to springs and seeps along the coast.

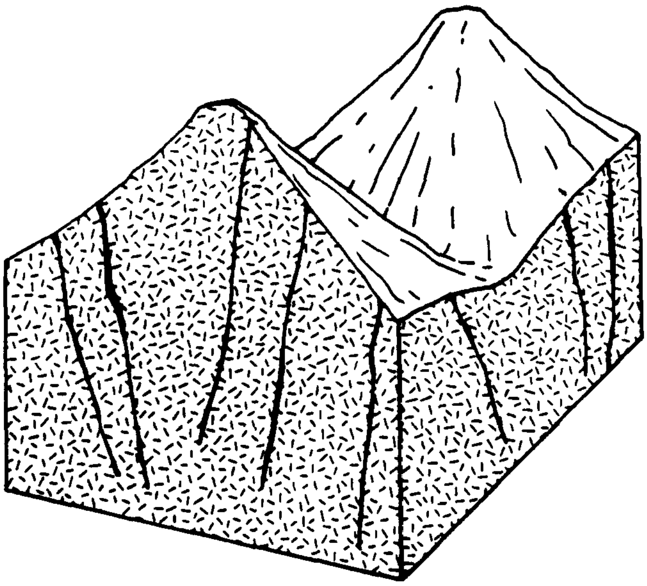
The basal water is the principal source of ground water on the islands. Because the freshwater is lighter (less dense) than seawater, it floats as a lens-shaped body on the underlying seawater. The thickness of the freshwater zone below sea level essentially depends on the height of the freshwater head above sea level. Near the coast the zone is thin, but several kilometers inland from the coast on the larger islands it reaches thicknesses of at least a few hundred meters. In parts of the coastal zone, and especially on the leeward side of the islands, the basal ground water is brackish.

Forty-six percent of the water used in Hawaii in 1975, or 3.1×10^6 $m^3 day^{-1}$, was ground water. It is obtained through horizontal tunnels and through both vertical and inclined wells. Tunnels are used to obtain supplies of basal water near the coast where the freshwater zone is thin. Tunnels are also used to tap dike-impounded water. These tunnels encounter large flows of water when the principal impounding dike is penetrated and it is necessary to drain most of the water in the saturated zone above the tunnel before construction can be completed. Thereafter, the yield of the tunnel reflects the rate of recharge to the compartment tapped by the tunnel. To avoid a large initial waste of water and to preserve as much storage as possible, the Honolulu Board of Water Supply has begun to construct inclined wells to obtain dike-impounded water. Vertical wells are used to obtain basal water and perched ground water in inland areas where the thickness of the freshwater zone permits the use of such wells.

Hawaii

(12A) Mountain Slopes

This hydrogeologic setting is characterized by steep slopes composed of volcanic lava flows, breccia, and related extrusive magmatic rocks. Soils are thin, but highly permeable where present. Rubble alluvial deposits are common. Because of the steep topography and elevation the water table tends to be deep. Water occurs in the fractures and vesicular zones of the basaltic lava flows, and along the relatively horizontal inter-flow zones. Overall, hydraulic conductivity is moderately high, due to the density of fracture zones. Perched water table zones are common, where water in an inter-flow zone between successive lava flows is delayed from moving downward by a dense layer of clayey material, or basalt. The dense layer acts as an aquitard. Rainfall is high, and with permeable surface material recharge is also high.



Hawaii

(12B) Alluvial Mountain Valleys

This hydrogeologic setting is characterized by narrow, steep-walled valleys, with moderate to steep seaward slope. The valleys contain alluvial material varying typically from zero to a few tens of feet in thickness. Waterfalls and related features are common near the ocean. The alluvium consists of basaltic debris and the weathered products thereof. Soils are moderately developed, thin, and quite permeable. Rainfall is high, infiltration, or recharge, is high, and vegetation is lush. The alluvium below stream grade is generally saturated at a shallow level, and is sometimes hydraulically connected to the permanent water table, sometimes to perched zones, and sometimes, particularly in the upper reaches, leaks into the vadose zone. Hydraulic conductivity of both the alluvium and underlying aquifers is high.

Setting 12 A Mountain Slopes

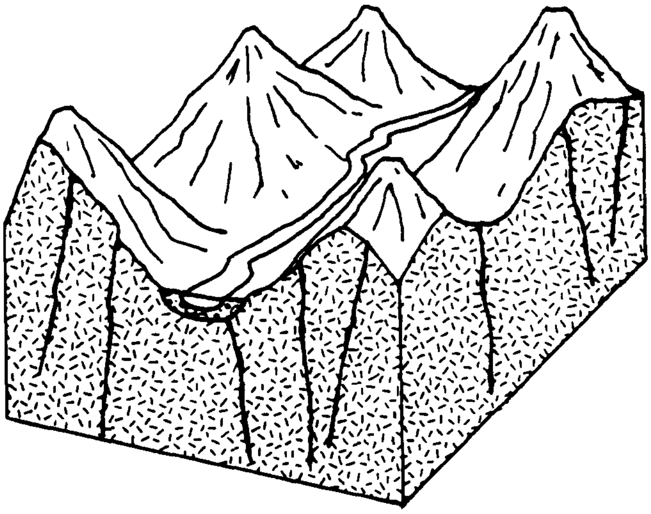
			General	
Feature	Range	Weight	Rating	Number
Depth to Water Table	100+	5	1	5
Net Recharge	10+	4	9	36
Aquifer Media	Basalt	3	9	27
Soil Media	Thin or Absent	2	10	20
Topography	18+%	1	1	1
Impact Vadose Zone	Basalt	5	9	45
Hydraulic Conductivity	2000+	3	10	30

DRASTIC Index 164

Setting 12 A Mountain Slopes

			Agricultural	
Feature	Range	Weight	Rating	Number
Depth to Water Table	100+	5	1	5
Net Recharge	10+	4	9	36
Aquifer Media	Basalt	3	9	27
Soil Media	Thin or Absent	5	10	50
Topography	18+%	3	1	3
Impact Vadose Zone	Basalt	4	9	36
Hydraulic Conductivity	2000+	2	10	20

Agricultural DRASTIC Index 177



Setting 12 B Alluvial Mountain Valleys

			General	
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	12-18%	1	3	3
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	1000-2000	3	8	24

DRASTIC Index 184

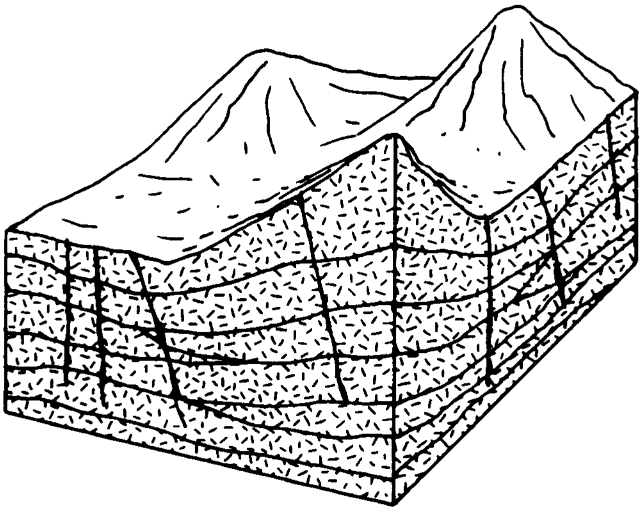
Setting 12 B Alluvial Mountain Valleys

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	12-18%	3	3	9
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	1000-2000	2	8	16
		Agricultural DRASTIC Index		192

Hawaii

(12C) Volcanic Uplands

This hydrogeologic setting is characterized by moderately rolling topography, at medium elevations, and rich, dark, soils developed from the basaltic bedrock. The soils are permeable, rainfall is high, and recharge is high. Bedrock is composed primarily of alternating extrusive basaltic lava flows and interlayered weathered zones formed between flows. Ground water occurs at moderate to deep depths, and aquifer yield is controlled by fracture zones, vesicular zones (both primarily cooling features) and the inter-flow weathered zones. Hydraulic conductivity is high. As with other settings in Hawaii, heavy pumping stresses often result in salt-water intrusion. This is a reflection of the fact that each island is surrounded by and underlain by salt water, with the fresh water occurring in a lenticular body that floats on the salt water. Ground-water yield is therefore limited quite specifically to the amount of water recharged annually.



Setting 12 C Volcanic Uplands

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	10+	4	9	36
Aquifer Media	Basalt	3	9	27
Soil Media	Sandy Loam	2	6	12
Topography	6-12%	1	5	5
Impact Vadose Zone	Basalt	5	9	45
Hydraulic Conductivity	2000+	3	10	30
		DRASTIC Index		165

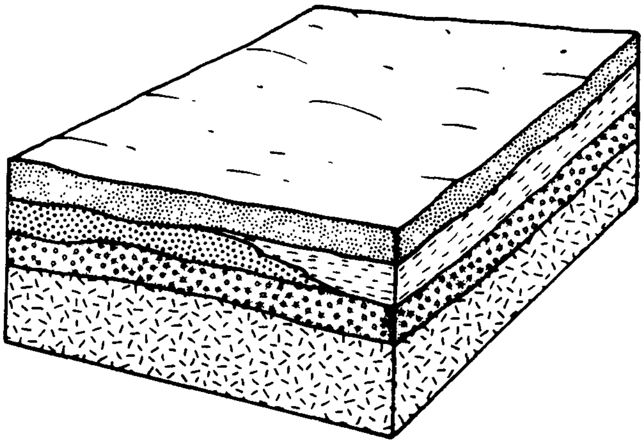
Setting 12 C Volcanic Uplands

		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	75-100	5	2	10
Net Recharge	10+	4	9	36
Aquifer Media	Basalt	3	9	27
Soil Media	Sandy Loam	5	6	30
Topography	6-12%	3	5	15
Impact Vadose Zone	Basalt	4	9	36
Hydraulic Conductivity	2000+	2	10	20
		Agricultural DRASTIC Index		174

Hawaii

(12D) Coastal Beaches

This hydrogeologic setting is characterized by low to moderate topography, near sea level, with sandy materials at the surface. The sandy soils are very permeable, and direct recharge from rainfall is high where ground-water levels permit. Because of their location these settings are often discharge areas where ground water is lost into the ocean. Management of this area is essential to the maximum utilization of the ground-water resources of the islands. It should be noted that all discharge areas are potential recharge areas, and as such potentially vulnerable to pollution.



Setting 12 D Coastal Beaches

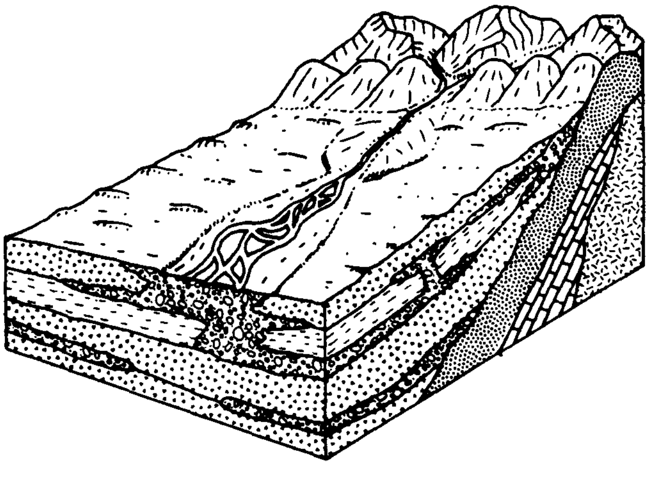
Feature	Range	General Weight	General Rating	General Number
Depth to Water Table	0-5	5	10	50
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	2	9	18
Topography	2-6%	1	9	9
Impact Vadose Zone	Sand and Gravel	5	8	40
Hydraulic Conductivity	1000-2000	3	8	24
			DRASTIC Index	201

Setting 12 D Coastal Beaches

Feature	Range	Agricultural Weight	Agricultural Rating	Agricultural Number
Depth to Water Table	0-5	5	10	50
Net Recharge	10+	4	9	36
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sand	5	9	45
Topography	2-6%	3	9	27
Impact Vadose Zone	Sand and Gravel	4	8	32
Hydraulic Conductivity	1000-2000	2	8	16
			Agricultural DRASTIC Index	230

13. Alaska

(Glacial and alluvial deposits, occupied in part by permafrost, and overlying crystalline, metamorphic, and sedimentary rocks)



The Alaska region encompasses the State of Alaska, which occupies an area of 1,519,000 km^2 at the northwest corner of North America. Physiographically, Alaska can be divided into four divisions—from south to north, the Pacific Mountain System, the Intermontane Plateaus, the Rocky Mountain System, and the Arctic Coastal Plain. The Pacific Mountain System is the Alaskan equivalent of the Coast Range, Puget Sound Lowland, and Cascade provinces of the Washington-Oregon area. The Intermontane Plateaus is a lowland area of plains, plateaus, and low mountains comparable to the area between the Cascades-Sierra Nevada and the Rocky Mountains. The Rocky Mountain System is a continuation of the Rocky Mountains of the United States and Canada, and the Arctic Coastal Plain is the geologic equivalent of the Great Plains of the United States and Canada. The coastal areas and lowlands range in altitude from sea level to about 300 m, and the higher mountains reach altitudes of 1,500 to 3,000 m. Mt. McKinley in the Pacific Mountain System is the highest peak in North America, with an altitude of about 6,300 m.

As would be expected of any area its size, Alaska is underlain by a diverse assemblage of rocks. The principal mountain ranges have cores of igneous and metamorphic rocks ranging in age from Precambrian to Mesozoic. These are overlain and flanked by younger sedimentary and volcanic rocks. The sedimentary rocks include carbonates, sandstones, and shales. In much of the region the bedrock is overlain by unconsolidated deposits of gravel, sand, silt, clay, and glacial till.

Climate has a dominant effect on hydrologic conditions in Alaska. Mean annual air temperatures range from -12°C in the Rocky Mountain System and the Arctic Coastal Plain to about 5°C in the coastal zone adjacent to the Gulf of Alaska. The present climate and the colder climates that existed intermittently in the past have resulted in the formation of permafrost, or perennially frozen ground. Permafrost is present throughout the State except in a narrow strip along the southern and southeastern coasts. In the northern part of the Seward Peninsula, in the western and northern parts of the Rocky Mountain System, and in the Arctic Coastal Plain, the permafrost extends to depths as great as 600 m and is continuous except beneath deep lakes and in the alluvium beneath the deeper parts of the channels of streams. South of this area and north of the coastal strip, the permafrost is discontinuous and depends on exposure, slope, vegetation, and other factors. The permafrost is highly variable in thickness in this zone but is generally less than 100 m thick.

Much of the water in Alaska is frozen for at least a part of each year: that on the surface as ice in streams and lakes or as snow or glacier ice and that below the surface as winter frost and permafrost. Approximately half of Alaska, including the mountain ranges and adjacent parts of the lowlands, was covered by glaciers during the Pleistocene age. About 73,000 km^2, or one-twentieth of the region, is still occupied by glaciers, most of which are in the mountain ranges that border the Gulf of Alaska. Precipitation, which ranges from about 130 mm yr^{-1} in the Rocky Mountain System and the Arctic Coastal Plain to about 7,600 mm yr^{-1} along the southeast coast, falls as snow for 6 to 9 months of the year and even year-round in the high mountain regions. The snow remains on the surface until thawing conditions begin, in May in southern and central Alaska and in June in the arctic zone. During the period of subfreezing temperatures, there is no overland runoff, and many streams and shallow lakes not receiving substantial ground-water discharge are frozen solid.

From the standpoint of ground-water availability and well yields, Alaska is divided into three zones. In the zone of continuous permafrost, ground water occurs beneath the permafrost and also in small, isolated, thawed zones that penetrate the permafrost beneath large lakes and deep holes in the channels of streams. In the zone of discontinuous permafrost, ground water occurs below the permafrost and in sand and gravel deposits that underlie the channels and floodplains of major streams. In the zone of discontinuous permafrost, water contained in silt, clay, glacial till, and other fine-grained deposits usually is frozen. Thus, in this zone the occurrence of ground water is largely controlled by hydraulic conductivity. In the zone not affected by permafrost, which includes the Aleutian Islands, the western part of the Alaska Peninsula, and the southern and southeastern coastal areas, ground water occurs both in the bedrock and in the relatively continuous layer of unconsolidated deposits that mantle the bedrock.

Relatively little is known about the occurrence and availability of ground water in the bedrock. Permafrost extends into the bedrock in both the zones of continuous and discontinuous permafrost, but springs that issue from carbonate rocks in the Rocky Mountain System indicate the presence of productive water-bearing openings. Small supplies of ground water have also been developed from sandstones, from volcanic rocks, and from faults and fractures in the igneous and metamorphic rocks.

Recharge of the aquifers in the Alaska region occurs when the ground is thawed in the areas not underlain by permafrost. This period generally lasts only from June through September. Because the ground, even in nonpermafrost areas, is still frozen when most snowmelt runoff occurs, relatively little recharge occurs in interstream areas by infiltration of water across the unsaturated zone. Instead, most recharge occurs through the channels of streams where they flow across the alluvial fans that fringe the mountainous areas and in alluvial deposits for some distance downstream. Because of the large hydraulic conductivity of the sand and gravel in these areas, the rate of infiltration is large. Seepage investigations along Ship Creek near Anchorage indicate channel losses of 0.07 m^3 sec^{-1} km^{-1}, which gives an infiltration rate through the wetted perimeter of about 0.4 m day^{-1}.

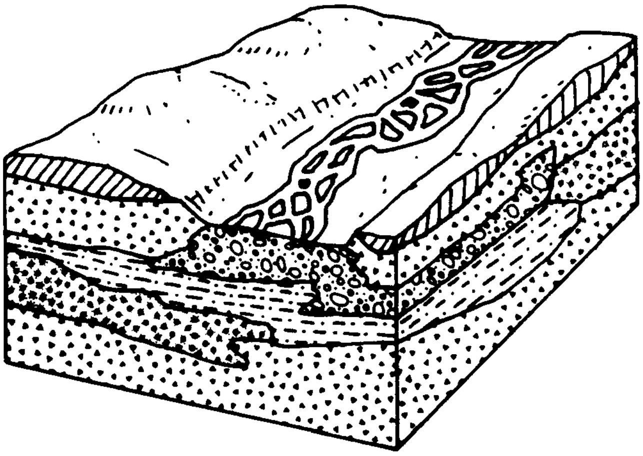
Discharge from aquifers occurs in the downstream reaches of streams and through seeps and springs along the coast. The winter flow of most Alaskan streams is sustained by ground-water discharge. In the interior and northern regions, this discharge is evidenced by the buildup of ice (referred to locally as "icings") in the channels of streams and on the adjacent floodplains.

Unlike the 12 regions which comprise the contiguous United States, both Alaska and Hawaii are political subdivisions, not discrete ground-water regions. Hawaii can be treated as a single region because of its smaller size and relative geologic simplicity. Alaska, however, due to its size and complexity includes several major ground-water regions. For purposes of this document, these regions are considered hydrogeologic settings.

Alaska

(13A) Alluvium

This hydrogeologic setting includes floodplains, terraces, and alluvial fans of both major valleys and upland and mountain valleys. Braided streams are present in the major valley floodplains. Heavy silt/rock flour loading in streams results in subtantial silt and clay deposition along with the alluvial sands and gravels. Ground-water levels are usually shallow near the streams, into which the ground water discharges, and considerably deeper along the higher terraces. Recharge to the ground water is seasonal, following snowmelt and thawing of frozen areas. Except for the south coastal area, precipitation is light to moderate and usually in the form of snow. Topography is moderate, with a unidirectional downstream ground-water movement. Hydraulic conductivities are moderate to very high in the cleaner portions of the sand and gravel aquifers.



Setting 13 A Alluvium

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	S & G w/sig. Silt and Clay	5	6	30
Hydraulic Conductivity	700-1000	3	6	18

DRASTIC Index 140

Setting 13 A Alluvium

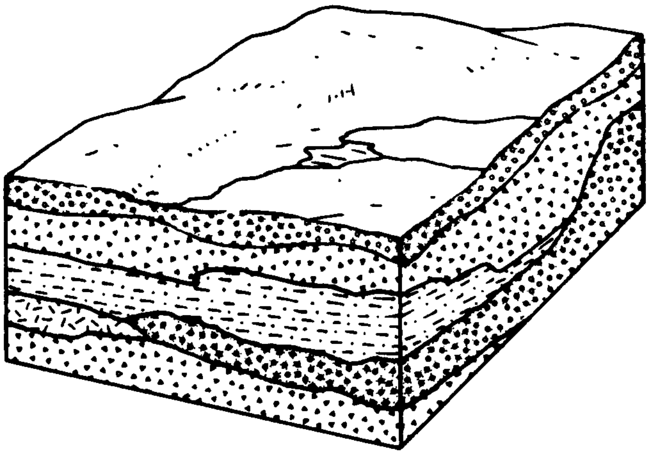
		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	1	9	27
Impact Vadose Zone	S & G w/sig. Silt and Clay	4	6	24
Hydraulic Conductivity	700-1000	2	6	12

Agricultural DRASTIC Index 164

Alaska

(13B) Glacial and Glaciolacustrine Deposits of the Interior Valleys

This hydrogeologic setting is characterized by tills and associated outwash deposits, as well as glacier-related lake deposits of interbedded sand, silt, and clay. Ground-water levels are relatively shallow. Surface soils are typically organic sandy loams with moderate conductivity. Recharge is moderate to low, primarily limited by the period of thaw and annual precipitation. Topography is moderate, and the hydraulic conductivity of the outwash aquifers is generally high.



Setting 13 B Glacial & Glaciolacustraine Deposits: Interior Valleys

		General		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	Silt/Clay	5	1	5
Hydraulic Conductivity	1000-2000	3	8	24

DRASTIC Index 131

Setting 13 B Glacial & Glaciolacustraine Deposits: Interior Valleys

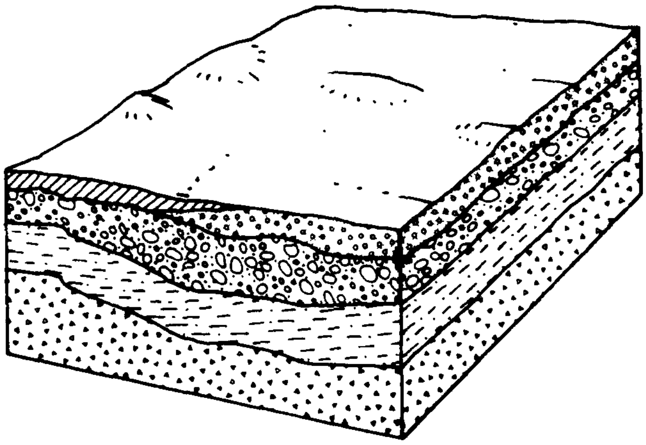
		Agricultural		
Feature	Range	Weight	Rating	Number
Depth to Water Table	5-15	5	9	45
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	Silt/Clay	4	1	4
Hydraulic Conductivity	1000-2000	2	8	16

Agricultural DRASTIC Index 158

Alaska

(13C) Coastal-Lowland Deposits

This hydrogeologic setting includes coastal plains, deltaic deposits of major streams, beaches and near-shore bars and spits, and deposits of deep alluvial coastal basins and valleys. Permafrost severely affects the northernmost portions of this setting, which is within the permanent permafrost zone. Where not permanently frozen, recharge rates are high seasonally, particularly along streams which are hydraulically connected to the ground water. Ground-water depths are at or near the elevation of the surface streams, and topographic slopes are low to moderate. The primary aquifers in this setting are the alluvial sands and gravels that are interbedded with silts and clays. Thick sequences of all types of materials are common.



Setting 13 C Coastal Lowland Deposits

Feature	Range	General		
		Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	2	6	12
Topography	2-6%	1	9	9
Impact Vadose Zone	S & G w/sig Silt and Clay	5	6	30
Hydraulic Conductivity	700-1000	3	6	18

DRASTIC Index 140

Setting 13 C Coastal Lowland Deposits

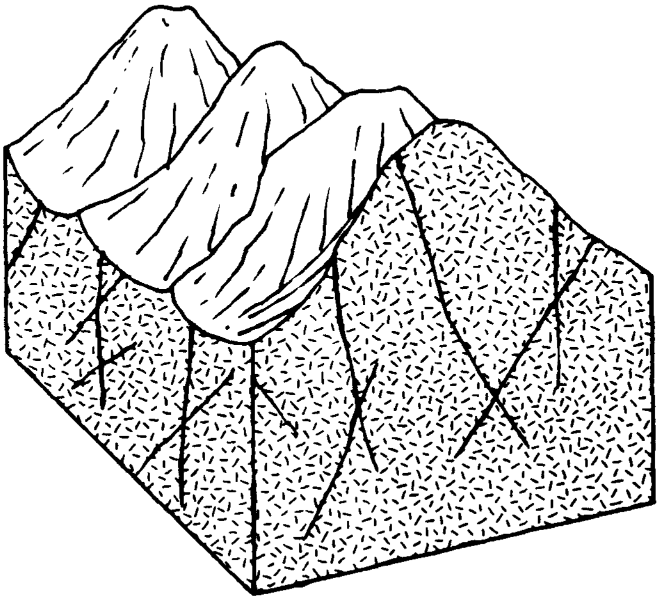
Feature	Range	Agricultural		
		Weight	Rating	Number
Depth to Water Table	15-30	5	7	35
Net Recharge	2-4	4	3	12
Aquifer Media	Sand and Gravel	3	8	24
Soil Media	Sandy Loam	5	6	30
Topography	2-6%	3	9	27
Impact Vadose Zone	S & G w/sig Silt and Clay	4	6	24
Hydraulic Conductivity	700-1000	2	6	12

Agricultural DRASTIC Index 164

Alaska

(13D) Bedrock of the Uplands and Mountains

This hydrogeologic setting is characterized by deposits of carbonate rocks, limestone, sandstone, volcanics, and other igneous and metamorphic rocks. These formations underlie a thin veneer of alluvium beneath a large portion of the state. Water levels within this setting are variable, but generally deep. Exceptions to this are discharge zones along the flanks of many mountains. The most notable example of this are springs discharging from carbonate rocks along the flanks of mountains. Recharge is limited by precipitation, topography, and predominant permafrost. Soils are generally thin and poorly developed. Aquifer conductivities vary from low in some of the fractured metamorphics to very high in the solution-dissolved carbonates.



Setting 13 D Bedrock of the Uplands and Mountains

Feature	Range	General Weight	 Rating	 Number
Depth to Water Table	100+	5	1	5
Net Recharge	0-2	4	1	4
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Thin or Absent	2	10	20
Topography	12-18%	1	3	3
Impact Vadose Zone	Bedded LS, SS, SH	5	6	30
Hydraulic Conductivity	300-700	3	4	12
		DRASTIC Index		92

Setting 13 D Bedrock of the Uplands and Mountains

Feature	Range	Agricultural Weight	 Rating	 Number
Depth to Water Table	100+	5	1	5
Net Recharge	0-2	4	1	4
Aquifer Media	Thin Bedded SS, LS, SH Sequences	3	6	18
Soil Media	Thin or Absent	5	10	50
Topography	12-18%	3	3	9
Impact Vadose Zone	Bedded LS, SS, SH	4	6	24
Hydraulic Conductivity	300-700	2	4	8
		Agricultural DRASTIC Index		118

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Appendix A

Processes and Properties Affecting Contaminant Fate and Transport

Most potential ground-water contaminants are released at or slightly above the water table as a result of various industrial, agricultural, and other human activities.

The attenuation of contaminants as they travel through the unsaturated zone and ground-water system is affected by a variety of naturally occurring physical processes and chemical reactions that often cause the contaminant to change its physical state or chemical form. This change may result in removal of the contaminant from the ground-water system. The extent of these reactions is dependent on hydrogeochemical conditions present in the ground water such as pH, redox-potential and solid surface area. However, the chemical processes within dynamic ground-water systems are complex, and are highly dependent on site-specific aquifer and soil characteristics as well as the effects of individual contaminants in the system (Cherry et al., 1984). Therefore, although the importance of these chemical reactions in attenuation of contaminants is widely recognized, prediction of the amount of attenuation of a contaminant in any environment is still very difficult.

Attenuation includes those mechanisms that lessen the severity or amounts of contaminants. The components which affect attenuation are the physical and chemical processes and properties including density, solubility, sorption, biodegradation, oxidation-reduction, dilution, hydrolysis, dispersion, viscosity, mechanical filtration, ion exchange, volatilization, and buffering or neutralization. The degree of attenuation that occurs is dependent on: (1) the time that the contaminant is in contact with the material through which it passes; (2) the grain size, and physical and chemical characteristics of the material through which it passes; and (3) the distance which the contaminant has traveled. For most materials, the longer the time, the greater the surface area and the greater the distance of travel, the greater the degree of attenuation. Movement of ground water is slower in rocks with high surface areas, such as found in a fine-grained porous medium, than in rocks where water movement is primarily through fault and fracture channels or solution openings. Additionally, flow velocity decreases with lower gradients and increasing depth; subsequently, ground water is in prolonged contact with rock materials (Matthess and Harvey, 1982).

Another factor affecting attenuation includes surface area in the aquifer media. The greater the surface area of the material through which the contaminant passes, the greater the potential for sorption of the contaminant. Likewise, the greater the reactivity of the material through which the contaminant passes, the greater the potential for attenuation.

The many physical processes and chemical reactions present in a ground-water system may work individually or in combination to provide varying degrees of attenuation depending on the hydrogeochemical conditions and the particular contaminant. The following discussion addresses each physical and chemical process and describes the respective impact on contaminants.

Density

The density of any substance is defined as mass per unit volume. The movement of a contaminant in an aquifer is directly affected by the density of the fluid with respect to the density of the ground water. Low density contaminants tend to float on top of the water table; high density contaminants tend to sink to the bottom of the aquifer.

Once a contaminant has entered an aquifer, it will be transported as a function of density in the direction of ground-water flow at a rate between a fraction of an inch a day to a few feet per day. Under the ideal condition of a homogeneous aquifer media, the contaminant will begin to disperse forming an elliptical plume (Pye et al., 1983; Todd, 1980). Movement and dispersion of the plume is affected by the density of the contaminant, the character of the geologic formation through which the contaminant passes and the reactive nature of the contaminant. In a uniform geologic formation, the more dense the contaminant, the greater will be the downward migration of that contaminant and the slower the contaminant will travel in relation to the velocity of ground-water flow.

Solubility

As a contaminant is introduced into an aquifer, the contaminant is generally partially dissolved in water, forming either miscible or immiscible solutions. A potential contaminant may also remain insoluble, depending on the chemical characteristics of the contaminant. The solubility of a substance is defined as the mass of a substance that will dissolve in a unit volume of solute under specified chemical conditions (Freeze and Cherry, 1979). The solubility of a constituent in water is dependent on variations in temperature, pressure, pH, redox potential (Eh), and the relative concentrations of other substances in solution. The interactions of these chemical parameters make it difficult to predict the solubilities of many substances in ground water (Davis and DeWiest, 1966; Snoeyink and Jenkins, 1980).

Substances are dissolved in water, or become soluble, because the water molecule exhibits a charge which tends to attract other molecules in solution. When the attractive forces that hold a substance together are less than or equal to the attractive force of the water molecule, the substance will dissolve. Conversely, those substances that are held together by attractive forces stronger than the attraction of the water molecule do not dissolve to any appreciable degree in water, thus forming immiscible liquids or solids. A good example is oil and water; the two substances do not mix because the oil is only slightly soluble in water. Substances that have been dissolved may be reprecipitated as a consequence of equilibria shifts and deposited in the void spaces of the aquifer. In addition, immiscible fluids may be transformed through similar changes in solubility.

The chemical reaction which transforms a dissolved substance to a solid form is precipitation. The precipitation of a dissolved substance may be initiated by changes in pressure, temperature, pH, concentration, or oxidation-reduction. In addition, the introduction of another substance that changes the equilibrium concentrations in the solution, or which reacts chemically with the dissolved substance may cause precipitation. The resultant solid is deposited in the void spaces of the aquifer, thereby reducing the space available for transport of the ground water.

Several types of contaminants can be effectively removed from the ground water through precipitation. Calcium salt solutions have been shown to effectively precipitate free fluorides (Tolman et al., 1978). Alkalis and/or sulfides may precipitate heavy metals. Stover and Kincannon (1983) have conducted successful experiments with regulated pH conditions, demonstrating the precipitation of metals using lime. Since oxidation-reduction reactions may change the chemical state of a substance by rendering it insoluble, this reaction has proven effective in changing dissolved chromium to a less soluble state thereby removing it from the ground water (Tolman et al., 1978; Fuller and Artiola, 1978). The FMC Corporation (1983) has conducted extensive studies using hydrogen peroxide to oxidize various sulfide compounds and initiate precipitation. Vapors escaping from a contaminated site may cause heavy metals to be transported and re-deposited. Each of these chemical reactions provides a method of changing the solubility of a substance, thereby removing the contaminant from the ground water and precipitating it in the void spaces of the aquifer. Even though the contaminant has changed form, the precipitate may be re-dissolved and the process repeated. When a precipitate re-dissolves, the contaminant may not be in its original form and may form a different solute which may or may not be harmless.

Sorption

Sorption is a combination of two processes, adsorption and absorption. Adsorption occurs when molecules or ions are attached to the surface of charged particles by weak Van der Waals or covalent bonds. Adsorption differs from absorption in that the latter involves penetration by the absorbed substance (Keenan and Wood, 1971; Matthess and Harvey, 1982). Sorption occurs on all surfaces where bonding conditions are present. Sorption increases with increasing surface area, which is usually a function of decreasing grain size. Colloidal particles range in diameter size from 10^{-3} to 10^{-6} mm. These particles tend to have a large charge relative to their surface area (Freeze and Cherry, 1979). Porous geologic materials that are composed of an appreciable amount of colloidal-sized particles exhibit a higher capability to sorb constituents onto the particle surfaces.

The subsurface materials that exhibit sorptive properties include clay minerals, hydrous iron, manganese, aluminum oxides, organic substances (particularly humus), glauconites and the rock-forming minerals mica, feldspar, aluminous augite and hornblende (Matthess and Harvey, 1982; Freeze and Cherry, 1979; Davis and DeWiest, 1966). These minerals are commonly present in colloidal form and contain especially large surface areas available for sorption.

The surface charge on a mineral in the saturated or unsaturated zone creates an attractive force. This charge may be due to (1) imperfections or substitutions in the crystal lattice of the particle or (2) chemical reactions at the surface of the particle involving weak hydrogen bonding, due to the presence of water. The pH of the water and the crystal structure of the mineral have a direct affect on the charge of the particle surface; waters with a high pH and highly crystalline materials typically produce net negative charges on the particle surface thus favoring the sorption of positive constituents or cations (Matthess and Harvey, 1982). There is a direct relationship between the quantity of a substance sorbed on a particle surface and the quantity of the substance suspended in solution. In general, an increase in the concentration of the substance in solution will increase the quantity sorbed.

The presence of organic materials in porous materials appears to be an important factor in the sorption of non-ionic organic substances. Those organic substances that are nonpolar (not attracted to water) and relatively insoluble tend to be readily sorbed by soils and sediments containing clays and organic carbon. The sorption of nonpolar aromatic and chlorinated hydrocarbons has been shown to increase with decreasing particle size and subsequently increasing organic carbon content (Karickhoff et al., 1979). Sorption of polar organics primarily occurs through weak hydrogen bonds to mineral particles (Cherry et al., 1984; Brown et al., 1983). Studies by Haque et al. (1974) and Griffen et al. (1978) indicate that sorption of PCBs was enhanced in materials with greater surface area and higher organic content. The sorptive capabilities of clays and soils appear promising for attentuation of some contaminants, however, further experimentation is necessary due to the complexity of chemical reactions that occur in the sorption process.

Ion Exchange

The process of ion exchange is similar to sorption, however, stronger ionic bonding occurs on the particle surfaces. Ion-exchange processes are virtually limited to colloidal size particles because these particles have large electrical charges with respect to their surface areas. Colloidal particles range in diameter size from 10^{-3} to 10^{-6} mm.

Ion exchange occurs when there is a surface charge imbalance. These surface charges are a result of (1) imperfections or ionic substitutions within the crystal or particle, or (2) chemical dissociation reactions at the particle surface. Upon exposure to water the charged molecules attract hydroxyl groups (OH^-) to the surface. When these hydroxyl groups break down, the resulting charge imbalance attracts oppositely charged particles (Freeze and Cherry, 1979). Ionic substitutions within particle surfaces also cause a charge imbalance that attracts oppositely charged ions. These ions comprise an adsorbed layer that is interchangeable; thus the process is reversible. An example of ionic substitutions occurs within silicate minerals. Aluminum ions tend to substitute for the silica ions, forming an unbalanced charge on the mineral surface. The nature of the surface charge that develops is dependent on pH; positively charged surfaces develop at low pH and a negatively charged surface prevails with a high pH. Clay minerals are the primary geologic materials of colloidal size that exhibit surface charges as a result of ionic substitutions. Organic materials such as humus and plant roots in soils and recent sediments also exhibit high ion-exchange capacities (Davis and DeWeist, 1966; Matthess and Harvey, 1982).

The most common ion exchange involves the transfer of cations on charged surfaces. Cation exchange capacity is the capability of a charged surface layer to attract positive ions in the zone adjacent to that charged surface (Freeze and Cherry, 1979). The affinity for attraction of cations varies with the valence, or charge, of the ion and the ionic size. Other things being equal, the affinity for ion exchange is greater when the ion has a higher valence. For ions of the same valence, the affinity for exchange increases with atomic number and decreases with increasing hydrate radius (Matthess and Harvey, 1982).

Other colloidal particles that exhibit ion-exchange capacities include hydrated oxides of iron and manganese. Hydrated oxides of iron selectively sorb zinc, copper, lead, mercury, chromium, molybdenum, tungsten, and vanadium through ion exchange. Similarly, hydrated oxides of manganese will bond to copper, nickel, cobalt, chromium, molybdenum, and tungsten (Matthess and Harvey, 1982). Clay minerals tend to preferentially bond zinc, copper, lead, mercury, and radioactive elements such as rubidium, cesium, and strontium. Certain organic dyes are firmly bonded to clays by strong electrostatic bonds (Matthess and Harvey, 1982). For cationic organic substances, increasing valence will tend to increase the capacity for bonding to clay surfaces, and vice versa for anionic organic constitutents (Brown et al., 1983).

Ion exchange can provide a means for attenuation of heavy metals and certain organic substances if the bonding is sufficiently strong to prevent reversal of the chemical reaction and release of the contaminant back into the ground-water system.

Oxidation-Reduction

Oxidation and reduction (redox) are geochemically important processes because together with pH, they control the solubility, and thus the presence of many substances in water. These reactions involve the transfer of electrons between dissolved, gaseous, and solid substances in the water. As a result of this electron transfer, there is a change in the oxidation state of the substance. A redox reaction consists of two parts or half reactions. In the oxidation reaction, the substance loses, or donates electrons; in the reduction reaction, the substance accepts, or gains electrons. Oxidation and reduction reactions are always coupled; no free electrons can exist in solution and electrons must be conserved (Snoeyink and Jenkins, 1980).

Deposits above the water table contain voids which are usually filled with atmospheric gases containing oxygen. Percolating water carries dissolved atmospheric oxygen to the water table where the processes of diffusion and dispersion can carry it to deeper water levels (Matthess and Harvey, 1982). The presence or absence of dissolved oxygen in the ground water is one factor which controls whether oxidizing or reducing conditions will predominate. Oxidation may be initiated in ground water by the presence or introduction of an oxidizing agent, such as potassium permanganate, or a change in valence state of ions such as Fe^{+3} and Mn^{+3}. In general, oxidation processes are increased in warm climates, and are more complete in humid and humid/arid climates than in arid climates.

Microorganisms are responsible for a large proportion of redox reactions which occur in ground water. The principal microorganisms involved in redox processes are bacteria which contain enzymes. Bacteria and their enzymes utilize redox processes to provide energy for cell synthesis and maintenance (Freeze and Cherry, 1979). Bacteria that require oxygen are known as aerobic bacteria, while anaerobic bacteria cannot tolerate dissolved oxygen in the water.

In many contaminated ground-water systems, dispersion exerts a strong influence on the redox state of the ground water. Dispersion causes a continuous mixing of waters that are different in chemical composition and redox potential. The mixing of these waters by dispersion affect the redox and pH conditions and may instigate other chemical reactions within the system.

The use of oxidation-reduction reactions for the attenuation of contaminants has proven effective for both inorganic and organic substances. The introduction of oxidizing agents into ground water is the most important mechanism of oxidation after microorganisms. Detoxification through oxidation of cyanides (Farb, 1978) and organic cyanides (Harsh, 1975) has been accomplished through the application of sodium hypochloride in conjunction with pH adjustments to produce substances that are insoluble. Dohnalek and Fitzpatrick (1983) documented removal of hydrogen sulfide from ground water in laboratory studies using oxidants. The FMC Corporation (1983) has conducted extensive experimentation using hydrogen peroxide to oxidize various sulfides and organic sulfides thereby rendering them insoluble. Certain organic compounds such as phenols, aldehydes, hydroquinine, as well as chlorine compounds and cyanides can also be ozidized by hydrogen peroxide (FMC, 1983). Matthess (1981) achieved treatment of arsenic-contaminated ground water by accelerating the natural precipitation process through the injection of the oxidant potassium permanganate. The soluble arsenic species was oxidized to the less soluble arsenate state and precipitated as iron and manganese arsenates and hydroxides, thus removing the arsenic from the ground water and eliminating the contamination problem. Injection of oxygenated water into an aquifer has also been shown to improve water quality by stimulating iron and manganese bacteria. The bacteria then provided the adsorption-oxidation mechanism that precipitated the iron and manganese hydroxides (Rott et al., 1981). Other chemicals susceptible to oxidation include phenols, aromatic amines, and dienes (Cherry et al., 1984). The application of a strong reducing agent has also proven effective in changing the oxidation state of chromium causing the formation of an insoluble chromium product.

The mechanisms of oxidation and reduction provide a means for reducing the solubility and causing subsequent precipitation through several reactions. Those most effective reactions for reducing solubility include a change in oxidation state, the formation of new compounds, and the enhancement of naturally occurring bacterial processes.

Biodegradation

Biodegradation results from the enzyme-catalyzed transformation of organic compounds by microbes, principally bacteria, fungi, actinomycetes, algae, and yeasts. Biological treatment can eliminate hazardous organic wastes by transforming them into innocuous forms, degrading them by mineralization to carbon dioxide and water, or by anaerobically decomposing them to carbon dioxide and methane (Kobayashi and Rittmann, 1982). Bacteria and other microbes require nutrients to produce the necessary enzymes that use or attack the organic compounds. Most microbes require oxygen, water, and nutrients such as carbon, nitrogen, phosphorus, and trace metals. Aerobic bacteria require the presence of free oxygen; anaerobic bacteria require the absence of dissolved oxygen. The metabolic processes of both types of bacteria are energy efficient and tend to enhance certain critical reactions. Reactions such as reductive dehalogenation, nitroreduction and reduction of sulfoxides are catalyzed by anaerobic bacteria (Kobayashi and Rittmann, 1982).

Biodegradation of a broad range of organic compounds particularly those that are man-made, have been demonstrated in laboratory studies. It is difficult to predict the exact transformations that may occur, due to the complexity of chemical reactions present in natural systems of mixed microbes and organic compounds (Cherry et al., 1984; Kobayashi and Rittmann, 1982). Biodegradation is dependent on interactions in a natural environment such as redox potential, dissolved oxygen, pH, temperature, presence of other compounds, salinity, other competing organisms, and the concentrations of compounds and organisms. Organic compounds need to be fairly soluble in water in order to be utilized by microbes.

Biodegradation can be limited if there are antagonistic interactions between two types of microbes, such as bacteria and fungi (Kobayashi and Rittmann, 1982). In addition, very low compound concentrations in a substrate may pose problems; certain organisms require minimal threshold values for survival and/or production of necessary enzymes.

Certain man-made organic compounds are refractory or resistant to biodegradation. This resistance is generally due to the presence of chemical substituents such as nitrogroups, chlorines, and amines, that are attached to the parent compound. Generally, larger molecules are less degradable than smaller ones (Kobayashi and Rittmann, 1982). Other important refractory compounds are halogenated organics which are very resistant to biodegradation (Brown et al., 1983). These halogenated organics include pesticides, plasticizers, solvents, and trihalomethanes. Chlorinated compounds such as DDT and other pesticides have been the most frequently studied compounds. The first step in degradation of halogenated organics involves dehalogenation by several biological mechanisms. Anaerobic reductive dehalogenation is an important mechanism in degradation of pesticides and certain halogenated aliphatic compounds.

Kobayashi and Rittmann (1982) and Tabak et al. (1980), indicate that most man-made organic compounds will undergo biodegradation to some extent. Actinomycetes and fungi are known to attack a wide variety of complex organic compounds. These microbes can grow under low nutrient conditions, wide temperature ranges and wide pH ranges. Actinomycetes break compounds down into groups that can be utilized by other organisms. Certain types of fungi are able to degrade complex hydrocarbons including the degradation of DDT. Fungi are believed to be capable of degrading PCBs more efficiently than bacteria (Gibson, 1978). Fungal metabolism is generally incomplete and requires other microbes for complete degradation. Bacteria have been found to degrade a wide variety of compounds under aerobic conditions. Bacteria are the major agents in the degradation of hydrocarbons and heterocyclic compounds (Kobayashi and Rittmann, 1982; Jhaveri and Mazzacca, 1983; Weldon, 1979; Tabak et al., 1980; Liu et al., 1981; Claus and Walker, 1964; Cherry et al., 1984).

Anaerobic bacteria degrade organic compounds to carbon dioxide and methane under oxygen-deficient conditions. Although little is known about these bacteria, four groups that utilize each of the metabolic products are responsible for degradation of the other groups. These bacteria are capable of dehalogenation, nitrosamine degradation, reduction of epoxide groups, reduction of nitro groups and the breakdown of aromatic structures (Kobayashi and Rittmann, 1982; Tabak et al., 1980). In a study conducted by Ehrlich et al. (1982) an aquifer contaminated by phenols and polynuclear aromatic hydrocarbons such as naphthelene showed significant reductions in these contaminants within 1000 m of the contamination source. Contaminant attenuation has been attributed to anaerobic degradation of the hydrocarbons by bacteria. Laboratory studies indicate that anaerobic bacteria are capable of degrading certain halogenated 1- and 2-carbon organic compounds such as trihalomethanes, chloroform, and trichloroethylenes (Bouwer et al., 1981).

Hydrolysis

The breakdown of substances under the influence of H^+ and OH^- ions in the water is known as hydrolysis. The breakdown of minerals by hydrolysis is an important reaction that occurs in the ground water, causing relatively insoluble minerals to form new minerals while releasing ions into solution. The hydrolysis process is dependent on pH, which controls the amounts of H^+ and OH^- ions in solution, in addition to the oxidation-reduction potential (Matthess and Harvey, 1982). Hydrolysis is most effective at high temperatures, low pH, and low redox potential. Hydrolysis is the basic reaction in the weathering processes which acts upon rocks and aids in the production of clays and soils.

Hydrolysis of an organic compound involves the introduction of a hydroxyl group (-OH) into the chemical structure, usually with the loss of a chemical group (X). The rate of hydrolysis of organic compounds is dependent on pH conditions and the presence of metal ions. A common hydrolysis reaction involves the replacement of halogens (X) by a hydroxyl group (Cherry et al., 1984). The occurrence of hydrolysis may aid in contamination attenuation. Certain organic compounds may be broken down by hydrolysis into simpler compounds that may then be easily assimilated through other processes. An example would be the hydrolysis of esters into a simple alcohol and acid that would comprise less harmful constituents in the ground water.

Hydrolysis is an important process in the attenuation of pesticides. It may be used to help predict the rate of decay of pesticides in the soil. (Cohen et al.,' 1984; Cherry et al., 1984). Hydrolysis of atrazine and other pesticide derivatives has been shown to operate faster when humic material is present. Hydrolysis rates for breakdown of pesticides have been determined for certain organic groups (Cherry et al., 1984; Callahan et al., 1979; Cohen, 1984).

Volatilization

Volatilization is defined as the loss of a compound to the atmosphere. This process provides an attenuation mechanism for those compounds that are resistant to degradation and/or weakly absorbed, and to those that exhibit low solubilities and high vapor pressures (Callahan et al., 1979; Brown et al., 1983). Organic constituents with high vapor pressures are more easily volatilized from the soil. Compounds that are not soluble tend to be available for volatilization longer because they are not readily removed by water. Persistent organic constituents that are not easily removed by other processes may tend to volatilize after a period of time. Organic compounds tend to volatilize more easily if they are less strongly sorbed by the soil.

Factors that affect volatilization include vapor pressure, water solubility, soil moisture, adsorption, wind speed, turbulence, temperature, depth below land surface and time (Brown et al., 1983; Callahan et al., 1979). Studies indicate that the highest volatilization of organics occurs within minutes of application and decreases substantially within one hour (Wetherold et al., 1981).

Volatilization of organics is generally restricted to the purgable or volatile organic compounds. These compounds include hydrocarbons, compounds with simple function groups such as alcohols, halides, and sulfur-containing compounds, and compounds containing unsaturated functional groups such as aldehydes, ketones, and esters. Increasing air humidity, soil temperature, and soil moisture have been shown to increase volatilization rates (Wetherhold et al., 1981).

Buffering and Neutralization

Buffering and neutralization are chemical reactions which are similar. Neutralization is achieved by balancing the pH or activity of the hydrogen ion concentration so that a neutral solution is produced. Buffering refers to the ability of a substance to maintain a constant pH over a wide range of concentrations. The neutralization of an acid or base produces water and neutral salts. Lime is effective in neutralization of acidic wastes.

Many biological processes rely on maintaining neutral pH levels to enhance biodegradation of organic constituents (Brown et al., 1983). Neutral pH levels are maintained in soils by their natural buffering capacity. Aluminum ions in the surface of clay colloids maintain an equilibrium of hydroxide ions in the soil solution. The actual pH range of a soil may vary according to the predominant clay constituent present (Brown et al., 1983). Neutralization of contaminants through pH adjustment is generally achieved by the addition of an acid or base, precipitation, and oxidation reduction.

A buffer solution is comprised of a weak acid or base plus a salt of that acid or base. A solution of this type will maintain a relatively constant pH even though a strong acid or base is added. A common example of this is the acetic acid-sodium acetate solution which will maintain a relatively constant pH when HCl is added, due to the H^+ ions from the HCl combining with the acetate ions, as follows:

$$\begin{array}{r} Na_2C_3H_2O \longrightarrow Na^{+} + \\ HCl \longrightarrow Cl^{-} + \end{array} \boxed{\begin{array}{l} C_2H_3O_2^{-} \\ H+ \end{array}} \begin{array}{l} \rightleftharpoons H_2C_2H_3O_2 \\ \end{array}$$

Therefore, no change occurs in the hydrogen ion concentration.

Carbonate systems provide very effective buffering systems in natural waters and waste waters (Snoeyink and Jenkins, 1980). The system is essentially based on a weak acid, carbonic, and sodium bicarbonate. As a consequence of the natural equilibria established between these parameters a relatively constant, near neutral pH is maintained for most ground waters, making many important biological processes possible.

The precipitation of chromium from water is directly controlled by variable pH values by providing suitable electron donors to change the chromium to a less soluble oxidation state (Tolman et al., 1978; Fuller and Artiola, 1978). The use of variable pH levels enables the detoxification of cyanide through oxidation and subsequent precipitation of insoluble cyanide compounds (Farb, 1978).

Dilution

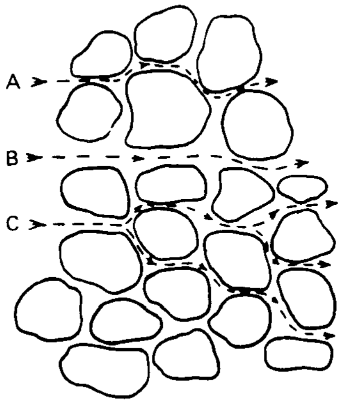
The dilution of ground-water contaminants occurs through the addition of water by precipitation or other sources, introduced into the ground-water system. Dilution is an integral mechanism of dispersion occurring on a microscopic and macroscopic scale (Todd, 1980). These mixing mechanisms produce longitudinal and transverse dispersion of the contaminant such that the concentration decreases with the distance from the point of introduction. According to Todd (1980), dilution may be the most important mechanism for attenuation after the pollutant enters the ground-water system.

Dispersion

A porous medium is composed of particles of varying sizes, shapes, and orientations. As water flows through a porous medium, the velocity varies across pore space and around particles. As a result, when a contaminant is introduced into a ground-water system, it tends to spread, or disperse, so as to gradually occupy an increasing volume of that flow system. Thus, dispersion constitutes a non-steady, irreversible mixing process by which the contaminant disperses within the surrounding ground water (Todd, 1980).

Dispersion has two components, longitudinal and transverse. Longitudinal dispersion occurs in the direction of flow and is caused by differences in macroscopic velocities as the water moves across pore spaces and around particles winding a tortuous path through the media in the direction of flow. Transverse dispersion occurs in two dimensions normal to ground-water flow and results from repeated division and deflection of the water flow by the particles (Todd, 1980; Bouwer, 1978). Figure A-1 illustrates transverse and longitudinal dispersion in a saturated porous medium.

Figure A-1 Schematic of pathlines showing longitudinal and transverse dispersion (Bouwer, 1978).



Longitudinal dispersion occurs when a contaminant enters at A or B.

Longitudinal and transverse dispersion occurs when a contaminant enters at C

Dispersion is a phenomenon that is caused by a combination of two processes, molecular diffusion and mechanical dispersion that occurs with laminar flow in a porous medium (Todd, 1980; Wilson et al., 1976). The result of these processes produces a contaminant plume with distinctly different characteristics dependent on the way the contaminant is introduced into the system. Figure A-2(a) illustrates the configuration of a plume that forms from the continuous input of contaminant, whereas Figure A-2(b) represents input of a contaminant in pulses. The contaminant plume developes an expanding elliptical shape with declining concentration per unit mass of aquifer because of the process of dispersion (Freeze and Cherry, 1979).

The relative rates of dispersion and the subsequent configuration of the contaminant plume are dependent on the homogeneity of the aquifer. Most laboratory testing of dispersion has been restricted to homogeneous, sandy mediums. Heterogeneous aquifer media present a complex dispersion pattern related to the respective hydraulic conductivities of the individual stratigraphic units. High conductivity units dominate the flow of contaminants in the ground-water system as well as provide zones of migration where contaminants would move more quickly than through adjacent units of low conductivity (Freeze and Cherry, 1979). The predomination of heterogenous geologic units that serve as aquifers has necessitated the quantification of contaminant transport through mathematical models (Freeze and Cherry, 1979; Bouwer, 1978; Roberts, 1981; Anderson, 1984). These models have been extended to include molecular diffusion, the adsorption of solutes by the media and the decay of radioactive materials. The primary emphasis of these models is to provide an effective means of predicting the extent of contaminant dispersion, contaminant flow velocities, and concentrations at various points within the plume. Most modeling efforts are constrained by the lack of adequate control data.

Viscosity

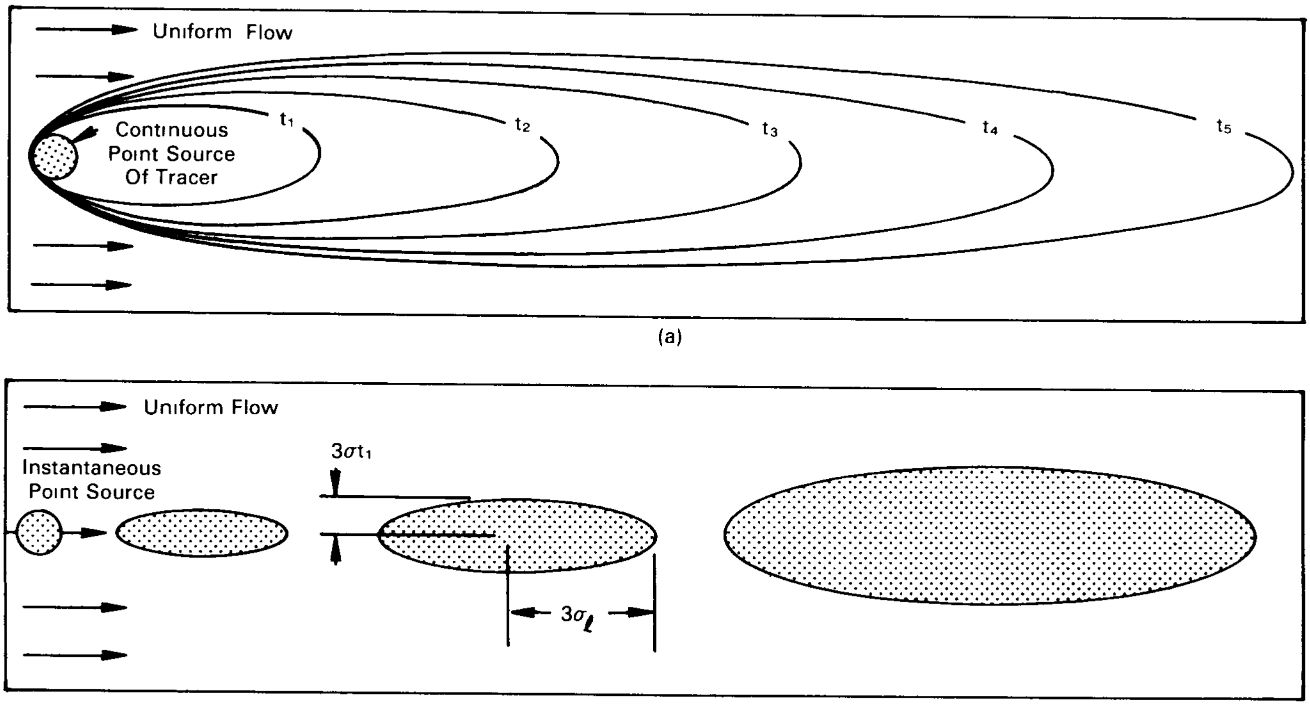
The viscosity of a fluid is the property of resistance to relative motion and shear deformation during flow. The more viscous the fluid, the greater the shear stress, and thus, the resistance to flow. Viscosity is affected by temperature; the higher the temperature, the lower the viscosity, and the easier it will be for a fluid to move through the pores in a media. Viscosity of water has a direct affect on hydraulic conductivity that can be quantified as an inverse linear relationship (Bouwer, 1978). Reducing the viscosity by half will double the hydraulic conductivity.

Thus, the viscosity of a contaminant will partially control the rate of migration. More viscous contaminants will not move as easily through porous media. Consideration of contaminant viscosity if it differs significantly from water viscosity, in conjunction with other applicable chemical reactions, may be necessary for prediction of contaminant migration.

Mechanical Filtration

Mechanical filtration removes contaminants which are larger than the pore spaces of the host medium. This process is most effective in finer-grained materials such as clay or soil, but can occur in coarse-grained media depending on the particulate sizes being filtered. The effects of mechanical filtration increase with decreasing pore and/or channel size within the media. Retention of larger particles may effectively reduce the permeability of the media. Chemical reactions such as precipitation may form larger, insoluble particles that are retained by the media, thereby affecting porosity and permeability. The effectiveness of mechanical filtration for removal of contaminants is thus dependent on grain size and sorting of the media, and hydraulic conditions within the media, and the particulate size of the contaminant being transported through the medium.

Figure A-2 Plume configuration based on contaminant input (Freeze and Cherry, 1979).



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Appendix B

Characteristics of Ground-Water Contaminants

Contaminants have been divided into inorganic compounds and organic compounds. For purposes of this discussion, inorganic compounds are subdivided into metals and nonmetals, while organic compounds are separated into groups bearing similar molecular structures which influence those processes affecting the fate and transport of ground-water contaminants.

Inorganic Metals

The mobility and attenuation of metals in any hydrogeologic setting is of function of the hydrochemical ground-water environment. Metals of primary importance include cadmium, chromium, copper, lead, mercury, manganese, silver, zinc, and iron for which maximum Federal Drinking Water Standards have been established. With the exception of iron, metals typically occur naturally in the environment in concentrations below 1 mg/l. Concentrations are low due to the processes of adsorption, hydrolysis, precipitation, and oxidation-reduction.

Metals tend to be hydrolized by water and exist as one or more ionic species. These metals combine readily with ligands to form ionic or neutral aqueous complexes. These ligands may be inorganic ions such as HCO_3^-, CO_3^{-2}, SO_4^{-2}, Cl^-, F^-, and NO_3^- (Freeze and Cherry et al., 1979). Any dissolved organic constituents that are present may also cause complexation or chelation. Increases in the concentrations of these anions increase the concentrations of the complexes that are formed. The occurrence of a complexed species is dependent on the pH and the equilibrium of a particular complex in the aqueous solution.

The oxidation-reduction potential of the ground water directly affects the oxidation state of the metal and may also affect the nonmetallic anions with which it forms complexes. Changes in the oxidation state of a metal may control the relative solubility or insolubility in water. The mechanism of sorption of trace metals is dependent on redox potential and pH.

Sorption of trace metals is an important process which may maintain metal concentrations far below that provided through solubility constraints. Trace-metal sorption occurs due to the presence of colloidal size clay particles, organic matter, and iron and manganese hydroxides. In most oxidizing environments, the iron and manganese oxides occur as surface coatings on grains thereby increasing their ability to sorb trace metals (Freeze and Cherry, 1979). This is particularly effective for Co, Ni, Cn, and Zn in soils and freshwater sediments.

The hydrochemical environment of a ground-water system exhibits many effects on trace metals making the prediction of transport and migration difficult and complex. In general, the processes of sorption and precipitation cause the trace metals to migrate very slowly with respect to ground water flow velocities. Thus, the occurrence of generally localized contamination by trace metals is common.

Cadmium (Cd)

Cadmium-contaminated wastes are generated as byproducts of cadmium-nickel battery production, pigments for plastics, enamels and paints, fumicides, and in electroplating and metal coatings. The solubility and sorption of cadmium are controlled by pH. Under acidic or low pH conditions, cadmium solubility increases while sorption by colloids decreases (Brown et al., 1983). Precipitation of cadmium carbonates and cadmium phosphates may reduce cadmium concentrations at low pH values. Precipitation of cadmium sulfides occurs in reducing environments. The primary mechanism for cadmium attenuation is through sorption to organic matter in soils as organic-metallic complexes. The contaminant level as established in the Federal Primary Drinking Water Standards is 0.01 mg/l.

Chromium (Cr)

Chromium is present in waste streams as a consequence of its use as a corrosion inhibitor, production of refractory bricks to line metallurgical furnaces, plating operations, topical antiseptics and astringents, and the tanning and dye industries (Brown et al., 1983). The oxidation-state of the chromium ion directly affects its toxicity; chromium is the most toxic and mobile at an oxidation state of +6. This is the most common form of chromium in industrial wastes, thus making chromium a concern. The soluble salts of chromium, such as sulfate and nitrate, are more toxic than the insoluble salts of oxides and phosphates. Under acid conditions, the presence of either oxygen or an oxidizing agent can change the oxidation state of chromium from +6 to +3 (Tolman et al., 1978; Fuller and Artiola, 1978). The +3 chromium is less toxic and generally immobile in ground water because it will readily precipitate with carbonates, hydroxides, and sulfides to form insoluble compounds. The maximum contaminant level as established in the Federal Primary Drinking Water Standards is 0.05 mg/l.

Copper (Cu)

Industrial wastes from textile mills, cosmetics manufacturing, and hardboard production contain significant amounts of copper. The sorption of copper onto colloids is a function of pH; sorption increases at higher pH values. Organic matter present in soils forms very stable complexes with copper (Brown et al., 1983). These include complexation with carboxyl and phenolic groups where sorption is high when iron and manganese oxide concentrations are low. Experiments indicate that copper is sorbed appreciably by quartz and even more strongly by clays. Copper is also beneficial because low concentrations are necessary for the metabolic processes of decomposition by bacteria. The maximum contaminant level as established in the Federal Secondary Drinking Water Standards is 1.0 mg/l.

Lead (Pb)

Lead is found in wastes from the manufacture of lead-acidic storage batteries, gasoline additives, ammunition, pigments, paints, herbicides, and insecticides. Lead may precipitate as sulfates, hydroxides, and carbonates. The presence of free lead ions depends on the stability of the lead complex at varying pH values. At high pH levels, lead is less soluble and preferentially sorbed onto clay surfaces. Under reduced conditions, lead becomes mobile and may form insoluble complexes with organic compounds (Brown et al., 1983). The maximum contaminant level as established in the Federal Primary Drinking Water Standards is 0.05 mg/l.

Mercury (Hg)

Mercury is present in a wide variety of industrial wastes such as electrical apparatus manufacturing, production of chlorine and caustic soda, pharmaceuticals, paints, plastics, paper products, and mercury batteries. Many pesticides have metals as part of their composition. Of these pesticides, over 40 percent use mercury as the major metal component (Brown et al., 1983). Mercury in the +2 oxidation state is rapidly and strongly complexed by covalent bonding to sulfur-containing organic compounds and inorganic soils. Colloidal particles of clay, iron and manganese oxides, fine sands, and organic matter readily absorb mercury. Sorption by clay particles is most effective at high pH values. The solubility of various mercury ionic complexes can be affected by changes in pH and/or oxidation-reduction. Insoluble precipitates of mercury, sulfates, hydroxides, and nitrates form at high pH conditions. Insoluble mercury sulfide occurs in reducing conditions, whereas, insoluble mercury chlorides favor oxidizing conditions.

Organic mercury compounds such as phenyl, alkyl, and methoxyethyl mercury used as fungicides may be degraded by certain bacteria. However, other bacterial forms tend to produce toxic mercury compounds with organic matter (Brown et al., 1983). The most toxic form of mercury occurs as methyl mercury and poses a contamination problem for the aquatic food chain. The maximum contaminant level as established in the Federal Primary Drinking Water Standards is 0.002 mg/l.

Manganese (Mn)

The major source of manganese-contaminated waste waters are from the iron and steel industries and from the manufacture of paints, disinfectants, and fertilizers. The manganese ion commonly occurs as Mn +2, which is soluble and mobile, and Mn +4, which is insoluble and thus non-mobile. Under reduced conditions, Mn +2 is strongly sorbed to clay minerals and organic matter, but becomes less soluble as pH increases. Under oxidizing conditions several stable manganese compounds will form (Brown et al., 1983). Manganese is considered a secondary constituent under Federal Drinking Water Standards; maximum contaminant levels are set at 0.05 mg/l.

Silver (Ag)

Silver is found in the waste streams of a variety of industrial processes including photographic, mirror, and electroplating manufacturing (Brown et al., 1983). Silver tends to be sorbed through ion exchange by colloidal particles and precipitated with common inorganic anions such as carbonate sulfates and chlorides. The maximum contaminant level as established in the Federal Primary Drinking Water Standards is 0.05 mg/l.

Zinc (Zn)

Industrial wastes containing zinc are a byproduct of brass and bronze alloy production, galvanized metals for pipes, utensils, insecticides, glues, rubber, inks, and glass (Page, 1974). Zinc can be attenuated through precipitation, absorption, and ionic substitution (Brown et al., 1983). Zinc may be ionically substituted for aluminum, iron, or magnesium in many clay minerals. Zinc is primarily sorbed onto organic colloids which are very soluble and mobile. Zinc may be sorbed onto the particle surfaces of alloys and is generally immobile. The solubility of zinc precipitates is dependent on the stability of the complex that forms under variable pH conditions. The only insoluble zinc precipitate is zinc sulfate. All other precipitates of zinc are soluble. Zinc is rendered insoluble in soils and water with a pH greater than 6.5. The maximum contaminant level as established in the Federal Secondary Drinking Water Standards is 5.0 mg/l.

Iron (Fe)

Iron, under oxidizing conditions in ground water, forms hydrous oxides which provide a major attenuation mechanism for the sorption of trace metals such as cobalt, nickel, copper, and zinc in soils and freshwater sediments. When this oxide occurs as coatings on grains of a media, it can greatly increase the sorptive capacity of that medium. Iron compound stabilities are dependent on pH and oxidation-reduction potential. Iron in reduced form is soluble and remains in solution. However, either very small-scale variations in the pH/Eh relationship or in bacterial activity can result in precipitation of iron in the hydrous oxide form. The maximum contaminant level as established in the Federal Secondary Drinking Water Standards is 0.3 mg/l. Unlike most other limits, the level for iron was not set because of associated health risks, but rather for water quality problems associated with staining and color. Iron oxides precipitate and stain due to their relative insolubility.

Inorganic Nonmetals

The chemical behavior of non-metallic substances in water has a significant effect on ground-water quality. Most non-metals tend to be fairly mobile in the ground-water system as ionic species. The type and amount of each species present is a function of temperature, pressure, pH, redox potential, dissolved concentrations, reactivity, and microbial activity.

The following discussion focuses on the major nonmetallic chemicals occurring in ground water. For each chemical, information is presented on the source(s) of the chemical and its water chemistry characteristics. These nonmetallic chemicals can occur either naturally in ground water or as a result of human activities.

Nitrogen

The most common inorganic contaminant is dissolved nitrogen in the form of nitrate (NO_3-). Dissolved nitrogen also occurs in the form of ammonium (NH_4+), ammonia (NH_3-), nitrite (NO_2-), nitrogen (N_2), and nitrous oxide (N_2O). Common sources of nitrate in ground water are from the burial of nitrogen-rich wastes, application of fertilizers, and disposal of sewage. When nitrogen-rich compounds are added to the environment, nitrogen is converted to different forms. The processes of nitrification (conversion of NH_4+ to NO_3- by oxidation) and ammonification (conversion of organic N to NH_4-) generally occur above the water table where oxygen and organic matter are abundant (Freeze and Cherry, 1979).

Concentrations of NO_3- are not limited by solubility. Thus, this anionic form is very mobile and stable under oxidizing conditions. NO_3- is not easily retarded or transformed by chemical processes. The presence of reducing conditions may initiate denitrification, a process where NO_3- is converted to N_2 or N_2O. These resulting forms are of less concern from a ground-water pollution standpoint because they pose no health risk. A maximum contaminant level of 10 mg/l N has been established for nitrates because of health concerns in infants when this level is exceeded.

Phosphorous

Phosphorous is not generally considered to be an intrinsically harmful constituent in ground water in normal concentrations, but its presence can cause significant environmental problems by decreasing available oxygen through accelerated algae and aquatic vegetative growth. The most common source of phosphorous contamination is by agricultural activity and decomposition of organic wastes. Dissolved phosphorous can occur in many forms depending on the pH of the water. Hydrolysis and mineralization can convert insoluble forms of phosphates to the soluble phosphate ion for use by plants and organisms (Brown et al., 1983). Degradation and mobilization of phosphorous by microbes accounts for a portion of its attenuation. Under certain conditions, phosphorous will precipitate as iron, aluminum, or calcium phosphate or be sorbed by iron and aluminum oxides and hydroxides.

Boron

Boron is released during the decomposition of organic materials. Partial sorption of boron may occur on iron and aluminum hydroxyl compounds and clays. The sorption of boron to these materials is pH dependent; sorption will not occur at high pH levels. The amount of boron that will be sorbed is dependent on surface area and appears to be irreversible due to the formation of covalent bonds. No drinking water standards for human consumption of boron have been set.

Sulfur

Sulfur is moderately abundant in the earth's soils and is an important plant nutrient. Sulfur, in some form, is widespread in industrial waste from processes such as Kraft mills, sugar refining, petroleum refining, and copper and coal extraction (Brown et al., 1983). Sulfur is commonly found in two forms; as sulfate (SO_4^{-2}) in oxidizing conditions, and as sulfide (HS^-) or (H_2S) under reducing conditions. Sulfides are toxic and produce an odor in water. The FMC Corporation (1983) has conducted extensive laboratory testing using hydrogen peroxide to oxidize sulfides to sulfur and water. Hydrogen peroxide has been shown to be effective in neutralizing other sulfur compounds that are common industrial waste effluents. These include polysulfides, sulfites, thiosulfates, polythionates, dithionites, and dithionates. Sulfates are relatively mobile in the ground-water system as anions. Some clays have the capability to sorb sulfate onto their particle surfaces (Brown et al., 1983). Sulfates also tend to form inorganic ligands and complex with metal ions increasing their solubility. A maximum contaminant level for sulfates is established in the Federal Secondary Drinking Water Standards at 250 mg/l.

Fluoride

The mobility of fluoride depends on the types and quantities of cations present in the water that have formed salts with the fluoride ion. Sodium salts of fluoride (NaF) have high solubilities as opposed to calcium salts (CaF_2) which have low solubilities. Fluoride may be a natural constituent of ground water produced from the dissolution of fluoride-bearing rocks or from industrial wastes such as the production of phosphatic fertilizers, hydrogen fluoride, and fluorinated hydrocarbons (Brown et al., 1983). Fluoride may also tend to complex with metallic ions. Soils with high cation exchange capacities are capable of retaining fluoride. The limit for concentration of fluoride has been established at 1.4 to 2.4 mg/l in the Federal Primary Drinking Water Standards.

Chloride

Chloride is very soluble and thus highly mobile in ground water. Chloride in ground water results from the dissolution of chloride-bearing rocks such as halite, and is a common product or byproduct (e.g. chlorinated hydrocarbon wastes) in most industrial wastes. Another source of chloride is from spillage or leakage of brines that are produced in oil and gas drilling operations. The maximum contaminant level as established in the Federal Secondary Drinking Water Standards is 250 mg/l.

Arsenic

Arsenic is contained in wastes from the production of herbicides, pesticides, pigments, and wood preservatives (Freeze and Cherry, 1979; Brown et al., 1983). Arsenic in natural ground water occurs in four oxidation states which exist as many different species under variable conditions. In general, most forms of arsenic tend to become soluble under oxidizing conditions. Solubility is controlled by pH and redox potential.

The movement of arsenic in the environment is affected by sorption to soils and volatilization. Sorption and/or precipitation by soil colloids is an important attenuation mechanism. These colloids include iron and aluminum hydroxides or clays. Sorption increases with increasing pH, clay, and hydroxide content. Levels of arsenic as low as 10 mg/l have been shown to be toxic (Brown et al., 1983). The maximum contaminant level as established in the Federal Primary Drinking Water Standards is 0.05 mg/l.

Selenium

Sources of selenium which can cause ground-water contamination include glass, electronics, steel, rubber, and photographic industries. Selenium has properties which are similar to sulfur. Selenium has three oxidation states. These typically form selenities and selanates of sodium and calcium, and soluble selenium salts. Selenium anions form selanates with mercury, copper, and cadmium which are very insoluble (Brown et al., 1983). Selenium in ground water is least soluble under acid conditions. Mechanisms for selenium attenuation include sorption onto hydrous iron oxides and precipitation to the insoluble ferric oxide selenite. The maximum contaminant level as established in the Primary Federal Drinking Water Standard is 0.01 mg/l.

Organic Compounds

The contamination of ground-water resources by organic compounds has resulted in the initiation of studies on their occurrence and behavior in the ground-water system. Many organic compounds of environmental concern are at trace levels, parts per billion or parts per million. However, even these minute levels may exhibit toxic effects on aquatic and mammalian life forms. The United States Environmental Protection Agency (EPA) has developed a list of what are considered to be the 129 priority pollutants and the relative frequency of these materials in industrial waste waters (Keith and Telliard, 1979) (Table B-1).

There are several chemical and biochemical reactions that are recognized as having a potential to significantly control contamination migration or attenuation in ground-water systems. These mechanisms include sorption, hydrolysis, oxidation-reduction, and biodegradation. A discussion of these processes is contained in Section 6, Processes and Properties Affecting Contaminant Fate and Transport.

The solubility of organic compounds may be divided into two broad groups; polar and nonpolar. Polar

Table B-1. EPA List of 129 Priority Pollutants and the Relative Frequency of These Materials in Industrial Wastewaters (Keith and Telliard, 1979)

Percent of samples[a]	Number of Industrial categories[b]		Percent of samples[a]	Number of Industrial categories[b]	
		31 are purgeable organics			
1.2	5	Acrolein	2.1	5	1,2-Dichloropropane
2.7	10	Acrylonitrile	1.0	5	1,3-Dichloropropane
29.1	25	Benzene	34.2	25	Methylene chloride
29.3	28	Toluene	1.9	6	Methyl chloride
16.7	24	Ethylbenzene	0.1	1	Methyl bromide
7.7	14	Carbon Tetrachloride	1.9	12	Bromoform
5.0	10	Chlorobenzene	4.3	17	Dichlorobromomethane
6.5	16	1,2-Dichloroethane	6.8	11	Trichlorofluoromethane
10.2	25	1,1,1-Trichloroethane	0.3	4	Dichlorodifluoromethane
1.4	8	1,1-Dichloroethane	2.5	15	Chlorodibromomethane
7.7	17	1,1-Dichloroethylene	10.2	19	Tetrachloroethylene
1.9	12	1,1,2-Trichloroethane	10.5	21	Trichloroethylene
4.2	13	1,1,2-Tetrachloroethane	0.2	2	Vinyl chloride
0.4	2	Chloroethane	7.7	18	1,2-trans-Dichloroethylene
1.5	1	2-Chloroethyl vinyl ether	0.1	2	bis(Chloromethyl) ether
40.2	28	Chloroform			
		46 are base/neutral extractable organic compounds			
6.0	9	1,2-Dichlorobenzene	5.7	11	Fluorene
		1,3-Dichlorobenzene	7.2	12	Fluoranthene
		1,4-Dichlorobenzene	5.1	9	Chrysene
0.5	5	Hexachloroethane	7.8	14	Pyrene
0.2	1	Hexachlorobutadiene	10.6	16	Phenanthrene
1.1	7	Hexachlorobenzene			Anthracene
1.0	6	1,2,4-Trichlorobenzene	2.3	6	Benzo(a)anthracene
0.4	3	bis(2-Chloroethoxy) methane	1.6	6	Benzo(b)fluoranthene
10.6	18	Naphthalene	1.8	6	Benzo(k)fluoranthene
0.9	9	2-Chloronaphthalene	3.2	8	Benzo(a)pyrene
1.5	13	Isophorone	0.8	4	Indeno(1,2,3-c,d)pyrene
1.8	9	Nitrobenzene	0.2	4	Dibenzo(a,h)anthracene
1.1	3	2,4-Dinitrotoluene	0.6	7	Benzo(g,h,i)perylene
1.5	9	2,6-Dinitrotoluene	0.1	2	4-Chlorophenyl phenyl ether
0.04	1	4-Bromophenyl phenyl ether	0	0	3,3'-Dichlorobenzidine
41.9	29	bis(2-Ethylhexyl) phthalate	0.2	4	Benzidine
6.4	12	Di-n-octyl phthalate	1.1	4	bis(2-Chloroethyl) ether
5.8	15	Dimethyl phthalate	0.8	7	1,2-Diphenylhydrazine
7.6	20	Diethyl phthalate	0.1	1	Hexachlorocyclopentadiene
18.9	23	Di-n-butyl phthalate	1.2	5	N-Nitrosodiphenylamine
4.5	12	Acenaphthylene	0.1	1	N-Nitrosodimethylamine
4.2	14	Acenaphthene	0.1	2	N-Nitrosodi-n-propylamine
8.5	13	Buty benzyl phthalate	1.4	6	bis(2-Chloroisopropyl) ether
		11 are acid extractable organic compounds			
26.1	25	Phenol	1.9	8	p-Chloro-m-cresol
2.3	11	2-Nitrophenol	2.3	10	2-Chloropenol
2.2	9	4-Nitrophenol	3.3	12	2,4-Dichlorophenol
1.6	6	2,4-Dinitrophenol	4.6	12	2,4,6-Trichlorophenol
1.1	6	4,6-Dinitro-o-cresol	5.2	15	2,4-Dimethylphenol
6.9	18	Pentachlorophenol			
		26 are pesticides/PCB's			
0.3	3	α-Endosulfan	0.3	3	Heptachlor
0.4	4	β-Endosulfan	0.1	1	Heptachlor epoxide
0.2	2	Endosulfan sulfate	0.2	4	Chlordane
0.6	4	α-BHC	0.2	2	Toxaphene
0.8	6	β-BHC	0.6	2	Aroclor 1016
0.2	4	δ-BHC	0.5	1	Aroclor 1221
0.5	3	γ-BHC	0.9	2	Aroclor 1232
0.5	5	Aldrin	0.8	3	Aroclor 1242
0.1	3	Dieldrin	0.6	2	Aroclor 1248
0.04	1	4,4'-DDE	0.6	3	Aroclor 1254
0.1	2	4,4'-DDD	0.5	1	Aroclor 1260
0.2	2	4,4'-DDT	—	—	2,3,7,8-Tetrachlorodibenzo-p-dioxin (TCDD)
0.2	3	Endrin			
0.2	2	Endrin aldehyde			

Table B-1. (Continued)

Percent of samples[a]	Number of Industrial categories[b]		Percent of samples[a]	Number of Industrial categories[b]	
			13 are metals		
18.1	20	Antimony	16.5	20	Mercury
19.9	19	Arsenic	34.7	27	Nickel
14.1	18	Beryllium	18.9	21	Selenium
30.7	25	Cadmium	22.9	25	Silver
53.7	28	Chromium	19.2	19	Thallium
55.5	28	Copper	54.6	28	Zinc
43.8	27	Lead			
			Miscellaneous		
33.4	19	Total cyanides		Not available	Asbestos (fibrous)
				Not available	Total phenols

[a] The percent of samples represents the times this compound was found in all samples in which it was analyzed for divided by the total as of 31 August 1978. Numbers of samples ranged from 2,532 to 2,998 with the average being 2,617.

[b] A total of 32 industrial categories and subcategories were analyzed for organics and 28 for metals as of 31 August 1978.

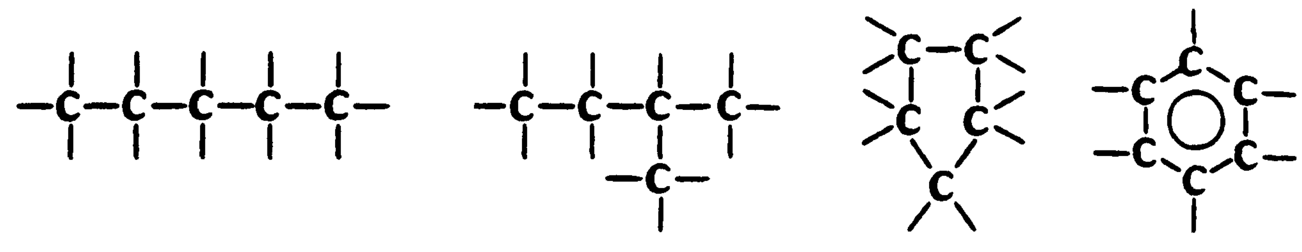
organics exhibit an affinity for water; and therefore do not bond or sorb to particle surfaces. Non-polar organics are not attracted to water and therefore tend to be easily sorbed. The solubility of an organic substance also affects its ability to be oxidized, hydrolyzed, and biodegraded. These properties differ between the organic groups and those interactions are often strongly dependent on the hydrogeochemical environmental factors including the pH, redox potential, and other constituent concentrations in the water.

The study of organic compounds, known as organic chemistry, deals with the compounds of carbon (Sawyer and McCarty, 1978). All organic compounds contain carbon in combination with one or more elements, most commonly, hydrogen, oxygen, nitrogen, phosphorous, and sulfur. Organic compounds generally exhibit several properties that make them different from inorganic substances. Organic compounds are generally combustible, less soluble in water, and have lower boiling and melting points. Reactions of organic compounds are generally molecular so they tend to be slower than most other chemical reactions. All organic compounds are either natural, synthetic, or fermentative in origin. Organic wastes are often produced from the processing of natural and synthetic organic materials and fermentation at industrial facilities.

The basis of an organic compound is the element carbon. Carbon is diverse because it maintains four covalent bonds in addition to the ability of the carbon atoms to link together by covalent bonding in a wide variety of ways (Sawyer and McCarty, 1978). These bonds may occur as a continuous chain, a branched chain, a cyclic ring, or as chains or rings containing other elements (Figure B-1). These structures serve as the basis for classification of organic compounds. For example, aliphatic compounds contain chains or branched chains of carbon atoms and aromatic compounds have carbon atoms linked in a six-member carbon ring which contains three double bonds that give them stability. Each of these compounds can be subdivided into groupings or homologous series where each member in the series differs from other members by the addition of an extra carbon group.

The naming of organic compounds is complex. The details of nomenclature may be found in a standard chemistry text or the CRC Handbook of Physics and Chemistry (Weast, 1983). The Office of Technology Assessment (1984) provides a comprehensive list of organic compounds that are known to occur in ground water, their ranges of detected concentrations,

Figure B-1 Covalent bonding arrangements of carbon atoms (Lippencott et al., 1978).



Straight Chain

Branched Chain

Ring

Aromatic Ring

examples of uses and quantitative estimates of carcinogenic potency, and noncarcinogenic toxicity (Table B-2). This list has been subdivided according to characteristic organic classes; aromatic hydrocarbons, oxygenated hydrocarbons, hydrocarbons with specific elements (N,S,P,Cl,I,F,Br) and "others." The "others" group generally corresponds to the aliphatic hydrocarbons which includes many petroleum products. The following discussions use this classification for simplicity, but expands upon the groups found within these classes.

Aliphatic Compound..

A hydrocarbon is a basic organic compound of carbon and hydrogen that may be of two types; saturated and unsaturated. A saturated hydrocarbon has adjacent carbon atoms joined by single covalent bonds with all other bonds to hydrogen atoms. Unsaturated hydrocarbons have at least two carbon atoms joined by more than one covalent bond with all other bonds satisfied by hydrogen (Sawyer and McCarty, 1978; Lippencott et al., 1978).

Saturated compounds range from a compound with one carbon atom, to those with each successive compound containing an additional carbon atom. These compounds are known as the alkanes or the methane series and are relatively inactive. The principal source of alkanes is petroleum. Mixtures of these compounds comprise gasoline and diesel fuel. Some other alkanes include ethane and propane. Methane is the simplest hydrocarbon (CH_4) and is a major end product of anaerobic treatment processes as well as a constituent of natural gas.

In the alkane series, butane has two isomers. An isomer is a compound that has the same molecular formula, but different structural formulas (Lippencott et al., 1973). Many organic compounds exhibit this property. Compounds containing rings of saturated carbon atoms are known as cycloalkanes; they are more reactive due to the strained structure of the small ring. These are commonly known as the napthenes and have cyclo-prefixes.

The unsaturated hydrocarbons can lose hydrogen to bond with other elements or compounds. The alkene or ethylene series of compounds all have one double bond between two adjacent carbon atoms. The compounds are commonly called olefins and are formed in large quantities during the processing of petroleum products. The most important reaction of the alkenes is polymerization, where small molecules unite to form giant molecules or polymers. The most common reaction is the polymerization of ethylene to form polyethylenes. The alkadienes or alkapolyenes contain more than two carbon-carbon double bonds. Those hydrocarbons containing triple bonds between carbon atoms are known as the alkyne or acetylene series. These compounds represent starting substances for many synthetic fibers.

Oxygenated Hydrocarbons

Oxygenated hydrocarbons refer to any organic compound that contains an (OH) group, an oxygen group, or responds as an acid in a solution. These may include both aromatic and aliphatic hydrocarbon groups.

Alcohols or hydroxy alkyl compounds are considered to be a step in the primary oxidation product of hydrocarbons. The alcohols are classified into three groups: primary, secondary, and tertiary, depending on the location of the (OH) group. The common alcohols are methyl, ethyl, isopropyl, and n-butyl. Methyl alcohol is used in the synthesis of organic compounds and in antifreeze. Ethyl alcohol is used in the production of beverages, synthesis of organic compounds, and in medicines. Isopropyl alcohol is used extensively in organic synthesis as is n-butyl alcohol. Short chain alcohols are soluble in water and may be volatized and biodegraded (Brown et al., 1983). Polyhydroxyl alcohols contain two hydroxyl groups per molecule and are known as glycols. These are commonly used as radiator anti-freeze compounds and are very toxic. Glycerol is a trihydroxy alcohol used extensively in soaps, foods, cosmetics, and medicines. Most alcohols are easily oxidized by oxidizing agents and many microorganisms. The aromatic alcohols compose a homologous series with the pre-word phenyl, for example phenyl methyl. These alcohols are also subject to chemical and biological oxidation.

Primary alcohols are oxidized to aldehydes, while secondary alcohols oxidize to ketones. Common aldehydes include formaldehyde and acetaldehyde. Formaldehyde is used extensively in organic synthesis and is toxic to microorganisms, however, under dilute concentrations it can be used as food by microorganisms and oxidized to carbon dioxide and water. The chemical names of all aldehydes end in -al. Many of the aromatic aldehydes exhibit fragrant odors, such as coumarin and vanillan. The ketones are used as industrial solvents and in the synthesis of organic products. The most common ketone is acetone. Both aromatic aliphatic ketones are easily oxidized by microorganisms.

Organic acids represent the highest oxidation state possible in an organic compound; further oxidation produces carbon dioxide and water (Sawyer and McCarty, 1978). All organic acids contain a carboxyl group. Thus, acids with one carboxyl group are known as monocarboxylic acids and so on. A wide variety of saturated and unsaturated acids occur in nature as constituents of waxes, fats, and oils. These are known as fatty acids which are typically straight chain

Table B-2. Substances Known to Occur in Ground Water, Ranges of Detected Concentrations, Exceeded Standards, Examples of Uses, and Quantitative Estimates of Carcinogenic Potency and Noncarcinogenic Toxicity (Ota, 1984)

Contaminant	Concentration	Standard	Examples of uses	Carcinogenic potency	Noncarcinogenic toxicity
Aromatic hydrocarbons	(parts per billion)				
Acetanilide	—		Intermediate manufacturing, pharmaceuticals, dyestuffs		
Alkyl benzene sulfonates	—	•	Detergents		
Aniline	—		Dyestuffs, intermediate, photographic chemicals, pharmaceuticals, herbicides, fungicides, petroleum refining, explosives		
Anthracene	18		Dyestuffs, intermediate, semiconductor research		
Benzene	0.6-20,230	★	Detergents, intermediate, solvents, antiknock gasoline	Low	
Benzidine	—		Dyestuffs, reagent, stiffening agent in rubber compounding	High	
Benzyl alcohol	—		Solvent, perfumes and flavors, photographic developer inks, dyestuffs, intermediate		
Butoxymethylbenzene	—		NA		
Chrysene	10		Organic synthesis		
Creosote mixture	—		Wood preservatives, disinfectants		
Dibenz[a.h.]anthracene	—		NA		
Di-butyl-p-benzoquinone	—		NA		
Dihydrotrimethylquinoline	—		Rubber antioxidant		
4,4-Dinitrosodiphenylamine	—		NA		
Ethylbenzene	0.9-4,000	★	Intermediate, solvent		Low
Fluoranthene	31	•	NA		
Fluorene	—		Resinous products, dyestuffs, insecticides		
Fluorescein	—		Dyestuffs		
Isopropyl benzene	290		Solvent, chemical manufacturing		
4,4'-Methylene-bis-2-chloroaniline (MOCA)	—		Curing agent for polyurethanes and epoxy resins	Low	
Methylthiobenzothiazole	—		—		
Napthalene	6.7-82	•	Solvent, lubricant, explosives, preservatives, intermediate, fungicide, moth repellant		Low
o-Nitroaniline	—		Dyestuffs, intermediate, interior paint pigments, chemical manufacturing		
Nitrobenzene	—		Solvent, polishes, chemical manufacturing		Moderate
4-Nitrophenol	—		Chemical manufacturing		
n-Nitrosodiphenylamine	—		Pesticides, retarder of vulcanization of rubber		
Phenanthrene	18-471		Dyestuffs, explosives, synthesis of drugs, biochemical research		
n-Propylbenzene	—		Dyestuffs, solvent		
Pyrene	48		Biochemical research		Low
Styrene (vinyl benzene)	—	•	Plastics, resins, protective coatings, intermediate		Low
Toluene	0.1-6,400	★	Adhesive solvent in plastics, solvent, aviation and high octane blending stock, dilutent and thinner, chemicals, explosives, detergents		
1,2,4-Trimethylbenzene	—		Manufacture of dyestuffs, pharmaceuticals, chemical manufacturing		
Xylenes (m,o,p)	0.07-300	•	Aviation gasoline, protective coatings, solvent, synthesis of organic chemicals		Low
Oxygenated hydrocarbons					
Acetic acid	—		Food additives, plastics, dyestuffs, pharmaceuticals, photographic chemicals, insecticides		Low
Acetone	10-3,000		Dyestuffs, solvent, chemical manufacturing, cleaning and drying of precision equipment		Low
Benzophenone	—		Organic synthesis, odor fixative, flavoring, pharmaceuticals		Low
Butyl acetate	—		Solvent		
N-Butyl-benzylphthalate	10-38		Plastics, intermediate		
Di-n-butyl phthalate	470	•	Plasticizer, solvent, adhesives, insecticides, safety glass, inks, paper coatings		Low
Diethyl ether	—		Chemical manufacturing, solvent, analytical chemistry, anesthetic, perfumes		
Diethyl phthalate	—	•	Plastics, explosives, solvent, insecticides, perfumes		
Diisopropyl ether	20-34		Solvent, rubber cements, paint and varnish removers		
2,4-Dimethyl-3-hexanol	—		Intermediate, solvent, lubricant		

Table B-2. (Continued)

Contaminant	Concentration	Standard	Examples of uses	Carcinogenic potency	Noncarcinogenic toxicity
2,4-Dimethyl phenol	—		Pharmaceuticals, plastics, disinfectants, solvent, dyestuffs, insecticides, fungicides, additives to lubricants and gasolines		
Di-n-octyl phthalate	23		Plasticizer for polyvinyl chloride and other vinyls		
1,4-Dioxane	2,100	★	Solvent, lacquers, paints, varnishes, cleaning and detergent preparations, fumigants, paint and varnish removers, wetting agent, cosmetics		
Ethyl acrylate	—		Polymers, acrylic paints, intermediate		
Formic acid	—		Dyeing and finishing, chemicals, manufacture of fumigants, insecticides, solvents, plastics, refrigerants		
Methanol (methyl alcohol)	—		Chemical manufacturing, solvents, automotive antifreeze, fuels		High
Methylcyclohexanone	—		Solvent, lacquers		
Methyl ethyl ketone	—		Solvent, paint removers, cements and adhesives, cleaning fluids, printing, acrylic coatings		
Methylphenyl acetamide	—		NA		
Phenols (e.g., p-Tert-butylphenol)	10-234,000	•	Resins, solvent, pharmaceuticals, reagent, dyestuffs and indicators, germicidal paints		
Phthalic acid	—		Dyestuffs, medicine, perfumes, reagent		
2-Propanol	—		Chemical manufacturing, solvent, deicing agent, pharmaceuticals, perfumes, lacquers, dehydrating agent, preservatives		
2-Propyl-1-heptanol	—		Solvent		
Tetrahydrofuran	—	Solvent			
Varsol	—		Paint and varnish thinner		
Hydrocarbons with specific elements (e.g., with N,P,S,Cl,Br,I,F)					
Acetyl chloride	—		Dyestuffs, pharmaceuticals, organic preparations		
Alachlor (Lasso)	190-1,700	★	Herbicides		Moderate
Aldicarb (sulfoxide and sulfone; Temik)	36-405	★	Insecticide, nematocide		High
Aldrin	—	•	Insecticides	High	
Atrazine	—	•	Herbicides, plant growth regulator, weed control agent		Moderate
Benzoyl chloride	—		Medicine, intermediate		
Bromacil	72-110	★	Herbicides		Moderate
Bromobenzene	1.9-5.8		Solvent, motor oils, organic synthesis		Moderate
Bromochloromethane	—		Fire extinguishers, organic synthesis		
Bromodichloromethane	1.4-110	★	Solvent, fire extinguisher fluid, mineral and salt separations		Low
Bromoform	2.4-110		Solvent, intermediate		Moderate
Carbofuran	4-160	★	Insecticide, nematocide		Moderate
Carbon tetrachloride	0.3-18,700	★	Degreasers, refrigerants and propellants, fumigants, chemical manufacturing	Moderate	
Chlordane	—	•	Insecticides, oil emulsions		
Chlorobenzene	2.7-41	•	Solvent, pesticides, chemical manufacturing		Moderate
Chloroform	1.4-1,890	★	Plastics, fumigants, insecticides, refrigerants and propellants		
Chlorohexane	—		NA		
Chloromethane (methyl chloride)	44		Refrigerants, medicine, propellants, herbicide, organic synthesis		Low
Chloromethyl sulfide	—	NA			
2-Chloronaphthalene	83		Oil: plasticizer, solvent for dyestuffs, varnish gums and resins, waxes Wax: moisture-, flame-, acid-, and insect-proofing of fibrous materials; moisture- and flame-proofing of electrical cable; solvent (see oil)		
Chlorpyrifos	—		NA		
Chlorthal-methyl (DCPA, or Dacthal)	—		Herbicide		
o-Chlorotoluene	2.4		Solvent, intermediate		
p-Chlorotoluene	—		Solvent, intermediate		
Dibromochloromethane	2.1-55		Organic synthesis		
Dibromochloropropane (DBCP)	1.-137	★	Fumigant, nematocide		
Dibromodichloroethylene	—		NA		

Table B-2. (Continued)

Contaminant	Concentration	Standard	Examples of uses	Carcinogenic potency	Noncarcinogenic toxicity
Dibromoethane (ethylene dibromide, EDB)	35-300	★	Fumigant, nematocide, solvent, waterproofing preparations, organic synthesis		
Dibromomethane	44.9		Organic synthesis, solvent		
Dichlofenthion (DCFT)	—		Pesticides		
o-Dichlorobenzene	2.7	•	Solvent, fumigants, dyestuffs, insecticides, degreasers, polishes, industrial odor control		Moderate
p-Dichlorobenzene	0.6-0.7	★	Insecticides, moth repellant, germicide, space odorant, intermediate, fumigants		Moderate
Dichlorobenzidine	—		Intermediate, curing agent for resins	Moderate	
Dichlorocyclooctadiene	—		Pesticides		
Dichlorodiphenyldichloroethane (DDD, TDE)	—		Insecticides		Low
Dichlorodiphenyldichloroethylene (DDE)	0.01-0.8		Degradation product of DDT, found as an impurity in DDT residues		
Dichlorodiphenyltrichloroethane (DDT)	0.05-0.22	•	Pesticides	High	
1,1-Dichloroethane	0.5-11,330		Solvent, fumigants, medicine		Low
1,2-Dichloroethane	250-847	★	Solvent, degreasers, soaps and scouring compounds, organic synthesis, additive in antiknock gasoline, paint and finish removers	Low	
1,1-Dichloroethylene (vinylidiene chloride)	1.2-4,000	★	Saran (used in screens, upholstery, fabrics, carpets, etc.), adhesives, synthetic fibers	Moderate	
1,2-Dichloroethylene (cis and trans)	0.2-323	★	Solvent, perfumes, lacquers, thermoplastics, dye extraction, organic synthesis, medicine		
Dichloroethyl ether	1,100		Solvent, organic synthesis, paints, varnishes, lacquers, finish removers, drycleaning, fumigants		
Dichloroiodomethane	2.8-4.1		NA		
Dichloroisopropylether (= bis-2-chloroisopropylether)	—		Solvent, paint and varnish removers, cleaning solutions		
Dichloromethane (methylene chloride)	4-8,400	★	Solvent, plastics, paint removers, propellants, blowing agent in foams		
Dichloropentadiene	0.36		NA		
2,4-Dichlorophenol	—	•	Organic synthesis		
2,4-Dichlorophenoxyacetic acid (2,4-D)	1-85,000	★	Herbicides		Moderate
1,2-Dichloropropane	46-60	★	Solvent, intermediate, scouring compounds, fumigant, nematocide, additive for antiknock fluids		
Dieldrin	—	•	Insecticides	High	
Diiodomethane	2.0		Organic synthesis		
Diisopropylmethyl phosphonate (DIMP)	—	•	NA		
Dimethyl disulfide	—		NA		
Dimethylformamide	—		Solvent, organic synthesis		
2,4-Dinotrophenol (Dinoseb, DNBP)	124-400		Herbicides		Moderate
Dioxins (e.g., TCDD)	—	★	Impurity in the herbicide, 2, 4, 5-T	High	
Dodecyl mercaptan (lauryl mercaptan)	—		Manufacture of synthetic rubber and plastics, pharmaceuticals, insecticides, fungicides		
Endosulfan	0.8	★	Insecticides		High
Endrin	—	•	Insecticides		High
Ethyl chloride	—		Chemical manufacturing, anesthetic, solvent, refrigerants, insecticides		
Bis-2-ethylhexylphthalate	12-170		Plastics	Low	
Di-2-ethylhexylphthalate	—	•	Plasticizers		
Fluorobenzene	67		Insecticide and larvicide intermediate		
Fluoroform	3.5		Refrigerants, intermediate, blowing agent for foams		
Heptachlor	—	•	Insecticides	Moderate	
Heptachlorepoxide	—	•	Degradation product of heptachlor, also acts as an insecticide		
Hexachlorobicycloheptadiene	2.2		NA		
Hexachlorobutadiene	2.53		Solvent transformer and hydraulic fluid, heat-transfer liquid		
α-Hexachlorocyclohexane (= Benzenehexachloride, or α-BHC)	6	★	Insecticides		

Table B-2. (Continued)

Contaminant	Concentration	Standard	Examples of uses	Carcinogenic potency	Noncarcinogenic toxicity
β-Hexachlorocyclohexane (β-BHC) β-BHC)	3.8	★	Insecticides		
γ-Hexachlorocyclohexane (γ-BHC, or Lindane)	0.5-43	★	Insecticides		Moderate
Hexachlorocyclopentadiene	—		Intermediate for resins, dyestuffs, pesticides, fungicides, pharmaceuticals		
Hexachloroethane	4.6		Solvent, pyrotechnics and smoke devices, explosives, organic synthesis	Low	
Hexachloronorbomadiene	—		NA		
Kepone	—	●	Pesticides		High
Malathion	—	●	Insecticides		
Methoxychlor	—	●	Insecticides		Moderate
Methyl bromide	7.4		Fumigants, pesticides, organic synthesis		
Methyl parathion	4.6	★	Insecticides		
Parathion	—	●	Insecticides		High
Pentachlorophenol (PCP)	—	●	Insecticides, fungicides, bactericides, algicides, herbicides, wood preservative		Moderate
Phorate (Disulfoton)	—	●	Insecticides		
Polybrominated biphenyls (PBBs)	—		Flame retardant for plastics, paper, and textiles		Low
Polychlorinated biphenyls (PCBs)	8-40	★	Heat-exchange and insulating fluids in closed systems	Moderate	
Prometon	—		Herbicides		
RDX (Cyclonite)	3,400	★	Explosives		
Simazine	—	●	Herbicides	Moderate	
Tetrachlorobenzene	5,000	★	NA		
Tetrachloroethanes (1,1,1,2 ¢ 1,1,2,2)	4	★	Degreasers, paint removers, varnishes, lacquers, photographic film, organic synthesis, solvent, insecticides, fumigants, weed killer	Moderate	
Tetrachloroethylene (or perchloroethylene, PCE)	717-2,405	★	Degreasers, drycleaning, solvent, drying agent, chemical manufacturing, heat-transfer medium, vermifuge	Low	
Toxaphene	1-570	★	Insecticides	Moderate	
Triazine	2		Herbicides		
1,2,4-Trichlorobenzene	37		Solvent, dyestuffs, insecticides, lubricants, heat-transfer medium (e.g., coolant)		
Trichloroethanes (1,1,1 and 1,1,2)	0.2-26,000	★	Pesticides, degreasers, solvent	Low	
1,1,2-Trichloroethylene (TCE)	210-37,000	★	Degreasers, paints, drycleaning, dyestuffs, textiles, solvent, refrigerant and heat exchange liquid, fumigant, intermediate, aerospace operations	Low	
Trichlorofluoromethane (Freon 11)	26		Solvent, refrigerants, fire extinguishers, intermediate		Moderate
2,4,6-Trichlorophenol	—		Fungicides, herbicides, defoliant		Low
2,4,5-Trichlorophenoxyacetic acid (2,4,5-T)	—	●	Herbicides, defoliant		Moderate
2,4,5-Trichlorophenoxypropionic acid (2,4,5-TP or Silvex)	—	●	Herbicides and plant growth regulator		High
Trichlorotrifluoroethane	35-135		Drycleaning, fire extinguishers, refrigerants, intermediate drying agent		
Trinitrotoluene (TNT)	620-12,600	★	Explosives, intermediate in dyestuffs and photographic chemicals		
Tris-(2,3-dibromopropyl) phosphate	—		Flame retardant		
Vinyl chloride	50-740	★	Organic synthesis, polyvinyl chloride and copolymers, adhesives	Low	
Other hydrocarbons					
Alkyl sulfonates	—		Detergents		
Cyclohexane	540		Organic synthesis, solvent, oil extraction		
1,3,5,7-Cyclooctatetraene	—		Organic research		
Dicyclopentadiene (DCPD)	—		Intermediate for insecticides, paints and varnishes, flame retardants		
2,3-Dimethylhexane	—		NA		

Table B-2. (Continued)

Contaminant	Concentration	Standard	Examples of uses	Carcinogenic potency	Noncarcinogenic toxicity
Fuel oil	—		Fuel, heating		
Gasoline	2,000-9,000	★	Fuel		
Jet fuels	—		Fuel		
Kerosene	243,000		Fuel, heating, solvent, insecticides		
Lignin	7,500i		Newsprint, ceramic binder, dyestuffs, drilling fuel additive, plastics		
Methylene blue activated substances (MBAs)	11	•	Dyestuffs, analytical chemistry		
Propane	—		Fuel, solvent, refrigerants, propellants, organic synthesis		
Tannin	7,500i		Chemical manufacturing, tanning, textiles, electroplating, inks, pharmaceuticals, photography, paper		
4,6,8-Trimethyl-1-nonene	—		NA		
Undecane	—		Petroleum research, organic synthesis		
Metals and cations	(parts per million)				
Aluminum	0.1-1,200	★	Alloys, foundry, paints, protective coatings, electrical industry, packaging, building and construction, machinery and equipment		High
Antimony	—		Hardening alloys, solders, sheet and pipe, pyrotechnics		Moderate
Arsenic	0.01-2,100	★	Alloys, dyestuffs, medicine, solders, electronic devices, insecticides, rodenticides, herbicides, preservative	High	
Barium	2.8-3.8	★	Alloys, lubricant		High
Beryllium	less than 0.01	★	Structural material in space technology, inertial guidance systems, additive to rocket fuels, moderator and reflector of neutrons in nuclear reactors	Moderate	
Cadmium	0.01-180	★	Alloys, coatings, batteries, electrical equipment, fire protection systems, paints, fungicides, photography	High	
Calcium	0.5-225		Alloys, fertilizers, reducing agent		
Chromium	0.06-2,740	★	Alloys, protective coatings, paints, nuclear and high-temperature research	High	
Cobalt	0.01-0.18	★	Alloys, ceramics, drugs, paints, glass, printing, catalyst, electroplating, lamp filaments		High
Copper	0.01-2.8	★	Alloys, paints, electrical wiring, machinery, construction materials, electroplating, piping, insecticides		Moderate
Iron	0.04-6,200	★	Alloys, machinery, magnets		
Lead	0.01-5.6	★	Alloys, batteries, gasoline additive, sheet and pipe, paints, radiation shielding		High
Lithium	—	•	Alloys, pharmaceuticals, coolant, batteries, solders, propellants		Low
Magnesium	0.2-70		Alloys, batteries, pyrotechnics, precision instruments, optical mirrors		
Manganese	0.1-110	★	Alloys, purifying agent		High
Mercury	0.003-0.01	★	Alloys, electrical apparatus, instruments, fungicides, bactericides, mildew-proofing, paper, pharmaceuticals		High
Molybdenum	0.4-40	★	Alloys, pigments, lubricant		
Nickel	0.05-0.5	★	Alloys, ceramics, batteries, electroplating, catalyst	Moderate	High
Palladium	—		Alloys, catalyst, jewelry, protective coatings, electrical equipment		Low
Potassium	0.5-2.4		Alloys, catalyst		
Selenium	0.6-20	★	Alloys, electronics, ceramics, catalyst		High
Silver	9-330	★	Alloys, photography, chemical manufacturing, mirrors, electronic equipment, jewelry, equipment, catalyst, pharmaceuticals		High
Sodium	3.1-211	★	Chemical manufacturing, catalyst, coolant, non-glare lighting for highways, laboratory reagent		
Thallium	—		Alloys, glass pesticides, photoelectric applications		High
Titanium	—		Alloys, structural materials, abrasives, coatings		Low
Vanadium	243	★	Alloys, catalysts, target material for x-rays		High, moderate
Zinc	0.1-240	★	Alloys, electronics, automotive parts, fungicides, roofing, cable wrappings, nutrition		Moderate

Table B-2. (Continued)

Contaminant	Concentration	Standard	Examples of uses	Carcinogenic potency	Noncarcinogenic toxicity
Nonmetals and anions					
Ammonia	1-900	★	Fertilizers, chemical manufacturing, refrigerants, synthetic fibers, fuels, dyestuffs		
Boron	—	•	Alloys, fibers and filaments, semi-conductors, propellants		
Chlorides	1.0-49,500	★	Chemical manufacturing, water purification, shrink-proofing, flame-retardants, food processing		
Cyanides	1.05-14	★	Polymer production (heavy duty tires), coatings, metallurgy, pesticides		High
Fluorides	0.1-250	★	Toothpastes and other dentrifices, additive to drinking water		Moderate
Nitrates	1.4-433	★	Fertilizers, food preservatives		
Nitrites	—	•	Fertilizers, food perservatives		
Phosphates	0.4-33		Detergents, fertilizers, food additives		
Sulfates	0.2-32,318	★	Fertilizers, pesticides		
Sulfites	—		Pulp production and processing food preservatives		
Micro-organisms	(parts per billion)				
Bacteria (coliform)	—	•			
Viruses	—				
Radionuclides	(picocuries per milliliter)				
Cesium 137	—		Gamma radiation source for certain foods		
Chromium 51	—		Diagnosis of blood volume, blood cell life, cardiac output, etc.		
Cobalt 60	6.4		Radiation therapy, irradiation, radiographic testing, research		
Iodine 131	—		Medical diagnosis, therapy, leak detection, tracers (e.g., to study efficiency of mixing pulp fibers, chemical reactions, and thermal stability of additives to food products), measuring film thicknesses		
Iron 59	—		Medicine, tracer		
Lead 210	—		NA		
Phosphorous 32	—		Tracer, medical treatment, industrial measurements (e.g., tire tread wear and thickness of films and ink)		
Plutonium 238,243	—		Energy source, weaponry		
Radium 226	0.8-25	★	Medical treatment, radiography		
Radium 228	12.5		NA		
Radon 222	—	•	Medicine, leak detection, radiography, flow rate measurement		
Ruthenium 106	—		Catalyst		
Scandium 46	—		Tracer studies, leak detection, semi-conductors		
Strontium 90	0.817	•	Medicine, industrial applications (e.g., measuring thicknesses, density control)		
Thorium 270	—		NA		
Tritium	150-353	•	Tracer, luminous instrument dials		
Uranium 238	10-500	★	Nuclear reactors		
Zinc 65	—		Industrial tracer (e.g., to study wear in alloys, galvanizing, body metabolism, function of oil additives in lubricating oils)		
Zirconium 95	—		NA		

structures. The lower members of the saturated acid series are liquids, ranging in order from the sharp odors of formic and acetic acid to the unpleasant odors of butyric and valeric acids. Butyric acid gives rancid butter its disagreeable odor. Industrial wastes from the dairy industry must be treated to prevent formation of these acids. These acids range from being completely soluble in water to relatively insoluble. The saturated acids include acrylic, oleic, and linoleic acids which are the general constituents of the glycerides of most fats and oils (Sawyer and McCarty, 1978; Lippencott et al., 1978). Organic acids are utilized by microorganisms through oxidation processes and are converted to carbon dioxide and water. Biodegradation of higher acids may be limited by their solubility in water. A wide variety of aromatic carboxylic acids are known such as benzoic acid, a preservative, salycilic acid, a constituent of aspirin, and phthalic acid, an important constituent in the manufacture of organic compounds. These acids are also subject to biodegradation by microorganisms to carbon dioxide and water.

The phenols are an important aromatic hydrocarbon. They consist of a basic ring hydrocarbon or benzene with an attached (OH) group. Phenols are generally known as carbolic acid which is widely used as a disinfectant, and in concentrated solutions is toxic to bacteria. Phenols occur as natural constituents of industrial wastes from coal and petroleum processing. Until recently, phenol was thought to be toxic to bacteria for biodegradation applications. However, current studies suggest that bacteria may be able to degrade low concentrations (Erlich et al., 1982; Tabak et al., 1980). Studies by the FMC Corporation (1983) indicate that hydrogen peroxide is capable of oxidizing phenols in the presence of a catalyst to produce carbon dioxide and water.

The next higher group of phenols are creosols. They are found in coal tar and exhibit even higher germicidal properties than phenols, but are less toxic. Creosols are commonly found in spray disinfectants such as lysol and in creosote, used in wood preservation. Phenols with more than one (OH) group are termed polyhydric. Three industrially important isomers of polyhydric phenols include the catechols, resorcinals, and hydroquinone. These isomers are readily oxidized by microorganisms (Sawyer and McCarty, 1978).

The degradation of aliphatic hydrocarbons by microorganisms depends on molecular weight, water solubility, number of double bonds, degree of branching, and whether the compound is an open chain or cyclic compound. Thus, the simplest compounds such as a straight chain hydrocarbon will be the most easily degraded as opposed to a more complex cyclic compound (Brown et al., 1983). The degradation rate decreases with either a decreasing number of double bonds or with the number and size of alkyl groups. Sediments containing aliphatic hydrocarbons are generally deficient in nitrogen and phosphorous. Addition of these fertilizers greatly enhances biodegradation rates (Brown et al., 1983). Volatilization of low molecular weight hydrocarbons is a mechanism that occurs with increasing temperature and soil moisture content.

Aromatic Compounds

The aromatic compounds contain stable ring structures, or cyclic groups, with special alternating single and double covalent bonds. These bonds are not normal. Thus, aromatic compounds do not bond to substances by addition, but rather by substitution of a hydrogen atom for an element or compound. The simplest aromatic ring is made up of a six-ringed carbon atoms bonded to six hydrogen atoms and is known as benzene or the benzene ring. Substitutions may occur at one or more hydrogen atom sites. The benzene series constitutes a single ring with alkyl substitutions; these include toluene and xylene and their respective isomers. These products are found in coal tar and crude petroleum and are used primarily as solvents.

A polyring aromatic hydrocarbon consists of one or more cyclic rings that are bonded through shared carbon atoms; these carbon atoms do not have attached hydrogen atoms. The polyring aromatic compounds include naphthelene and anthracene used in the manufacture of dyes, and phenanthracene, an important constituent of alkaloids such as morphine and vitamin D. Halogenated and nitrogenous aromatics will be discussed in the next section.

Aromatic compounds are usually present in wastes generated by petroleum refineries, organic chemical plants, rubber industries, and waste streams associated with combustion processes (Brown et al., 1983). Most aromatic hydrocarbons are toxic and/or carcinogenic and fairly resistant to degradation. The decomposition rate of aromatic hydrocarbons is basically substance dependent, however, simple compounds typically degrade more easily. In addition, the more soluble compounds are more easily degraded by microorganisms (Tabak et al., 1980).

Hydrocarbons with Specific Elements

The final group of hydrocarbons may be either aliphatic or aromatic, but has one or more additional groups with specific elements as substituents, namely nitrogen, sulfur, and phosphorous and the halogens, chlorine, fluorine, iodine and bromine. The halogenated organics have received the most attention as ground-water contaminants. These compounds are refractory, or very resistant to degradation. This is thought to be due to the presence of a halogen; its location and type determine the relative persistance of the compound (Kobayashi and Rittmann, 1982). These compounds range from simple alkyl halides to polyhalogen compounds to complex halogenated hydrocarbons such as DDT. Common halogenated compounds include methyl chloride, ethyl chloride, ethylene bromide, chloroform, carbon tetrachloride, chlorobenzene, freon (dichlorodifluoromethane) and trihalomethanes. Methyl and ethyl chloride were once used as refrigerants; ethyl chloride is used in the manufacture of tetraethyl lead, an antiknock gasoline additive. Chloroform has been found in drinking water due to the reaction of chlorine with natural organic substances in water. Freon is an extensively used refrigerant due to its non-toxic and non-flammable properties (Sawyer and McCarty, 1978).

Chlorinated hydrocarbons were formerly used extensively as pesticides and herbicides, many of which are very resistant to degradation. These include dioxin, DDT, DDE, Aldrin, Dieldrin, Endrin, Lindane, Chlordane, Toxaphene, 2,4-D and 2,4,5 TP Silvex which have been banned from usage or greatly restricted because of their toxicity and carcinogenic potentials (Solomons, 1978; Brown et al., 1983; Abrams et al., 1975). These products were used extensively for agricultural and defoliant purposes. Other pesticides and herbicides have been studied to determine their potential for attenuation through hydrolysis, reductive dehalogenation, and biodegradation.

Hydrolysis involves the introduction of an (OH) group that commonly replaces the halide. Hydrolysis rates are dependent on pH, the presence of humic materials, and individual compounds (Cherry et al., 1984; Cohen et al., 1984). Reductive dehalogenation involves the removal of the halogen through oxidation-reduction reactions in low redox state ground water (Cherry et al., 1984) and by certain microorganisms (Kobayashi and Rittmann, 1982). Biodegradation of halogenated hydrocarbons has been documented under both aerobic and anaerobic conditions (Kobayashi and Rittmann, 1982; Cherry et al., 1984; Bouwer et al., 1981; Tabak et al., 1980; Brown et al., 1983).

Other types of pesticides include organic phosphorous and carbomate pesticides. Organic phosphorous pesticides include parathion, which is very toxic, and malathion which has low toxicity for mammals. Phosphorous pesticides tend to hydrolyze quickly at or above a neutral pH, thus losing their toxic properties. The carbamates have generally low toxicities to mammals. These include IPC, a herbicide, captan, a fungicide, and ferbam and sevin as insecticides. These pesticides are highly susceptible to degradation (Sawyer and McCarty, 1978).

As a rule, chlorinated aromatics are less degradable and less soluble than their aliphatic counterparts. This has proven true for the chlorinated benzenes including hexachlorobenzene (HCB) and its derivatives. These are found as by-products of industrial processes, and in chlorinated solvents and pesticides. The rates of degradation of these compounds are slow; they may persist in the soil and water for several years without significant degradation. Certain plants such as lettuce, carrots, grasses, and potatoes tend to absorb HCBs from the soil (Brown et al., 1983). Rates of degradation are variable depending on the degree of chlorination; the less chlorinated, the more degradabale (Tabak et al., 1980).

Another widely publicized group of halogenated organics are the polychlorinated biphenyls (PCBs). These are biphenyl molecules with the presence of one or more chlorine atoms at several locations on the phenyl structures. These mixtures have been commercially produced since 1929 with a total of 210 possible compounds. PCBs are classified according to chlorine content with most industrial mixtures containing 40 to 60 percent chlorine (Solomons, 1980).

PCBs had many uses including heat exchangers in transformers, in capacitors and thermostats, plasticizers in food bags and polystyrene cups, in printing inks, and in waxes. Because the PCBs are highly persistent and fat soluble, they tend to collect in the tissues of many animals and humans. The EPA banned the manufacture, processing, and distribution of PCBs in 1979 (Solomons, 1980).

Degradation of PCBs has been found to be affected by the nature of the chlorine (Brown et al., 1983). Degradation tends to increase as the amount of chlorine substitution decreases; the relative position of the chlorine also affects rates of degradation. In general, the lower chlorinated compounds were found to be degradable in mixed microbial populations (Kobayashi and Rittmann, 1982).

Other hydrocarbons with specific elements have the nitrogen group as substituents. These include the amines, amides, anilines, and nitriles. The amines are alkyl derivatives of ammonia and may be primary, secondary, or tertiary depending on the number of hydrogen ammonia atoms that are replaced. The amines are found in industrial wastes from fish and beet-sugar industries, and little is known about their susceptibility to biodegradation. The amides are derived from organic acids and ammonia under special conditions. The nitriles are organic cyanides that are extensively used in the manufacture of synthetic fibers (Sawyer and McCarty, 1978). The most commonly used nitriles include acrylonitrile and acetonitrile. Attenuation of nitriles occur through oxidation reactions at specified pH values (Harsh, 1975). The primary form of amines are known as analines and are important compounds for organic synthesis and in dyes. The amines were shown to range in ease of biodegradability depending on the individual compound (Tabak et al., 1980; Kobayashi and Rittmann, 1982).

Mercaptans or thiols are aliphatic compounds that contain sulfur and they have a structure similar to alcohols. Mercaptans are known to have disagreeable odors and are typically byproducts of kraft pulping and petroleum processing. The FMC Corporation (1983) has shown that thiols are readily oxidized under acid conditions to insoluble products.

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Appendix C

Sources of Ground-Water Contamination

The quality of the ground water may be altered by a wide variety of human activities and naturally occurring phenomena. The innumerable waste materials and byproducts of man's activities provide potential for ground-water contamination through a variety of mechanisms.

Ground water quality problems that are attributed to man's influence are commonly related to: (1) water-soluble products that are placed on the land surface and in streams or surface impoundments, (2) substances that are deposited in the ground above the water table, and (3) disposal, storage, or extraction of materials below the water table (Lehr et al., 1976). Sources of ground-water pollution are associated with a broad range of industrial, agricultural, commercial, and domestic activites. Many of the problems that arise from wastes as a result of these activities are not well understood, due to their complexity. Technical solutions are available for many ground water quality problems through planning, management, and/or prevention practices.

The application of a rating system designed to estimate potential for ground-water contamination is of concern with regard to individual contamination situations. Because ground-water contamination may occur from a variety of sources, it may be necessary to consider and possibly reevaluate the importance of a rating factor as the scale of the area being evaluated changes.

Soil attenuation characteristics such as sorptive capabilities, microorganisms, degradation capacities, and textures are of major importance when considering the placement of wastes on the land's surface (e.g. stockpiles, sludge, wastewaters) and the subsequent potential for ground-water pollution. However, the effect of soil is relatively unimportant for situations where the soil has been removed, such as at a landfill, or where contaminants are buried beneath the soil surface (e.g. storage tanks). Thus, engineering and other practical considerations of an area can obviate the application of DRASTIC parameters.

Dry contamination sources that are emplaced on the land surface, such as stockpiles, fertilizers, and pesticides are dissolved and disseminated by rainfall resulting in the generation of ground-water pollution. Evaluation of the DRASTIC parameters suggests that the most important parameters with regard to this category of activities are: Depth to Water, which controls contact time of the pollutant with the unsaturated zone; Net Recharge, which limits the quantity of leachate generated; Soil Media, which affects both organic and inorganic attenuation mechanisms; and the Vadose Zone, which also directly affects attenuation properties. Parameters of lesser impact for this category of activities include: Aquifer Media and Hydraulic Conductivity, since these are impacted less by surface-applied pollutants. Topography may be important for surface storage facilities, but most agricultural activities are confined to relatively flat terrain.

Wet contamination sources emplaced on the land surface include waste waters, irrigation waters, and spills. In this situation, the most important parameters are Depth to Water, Soil Media, Impact of the Vadose Zone, and Topography which will affect the attenuation and infiltration rates of the liquid contaminants. Again, because the source is on the surface, Hydraulic Conductivity and Aquifer Media are less important. Net recharge has a less negative effect since the contaminant is already liquid. High net recharge may result in dilution.

This type of rationale can also be applied to either liquid or dry sources emplaced below the surface which may or may not intersect the water table. The potential for liquid sources below the water table to cause contamination, such as leaking underground storage tanks or drainage wells, is affected primarily by the Depth to Water, the Impact of the Vadose Zone, Hydraulic Conductivity, and the Aquifer Media. These factors are directly related to attenuation and migration rates of the contaminant. Surface characteristics such as Topography, Net Recharge, and Soil Media would subsequently be of lesser importance for potential pollution evaluations.

Lastly, for dry contaminant sources emplaced below the surface (e.g. landfills, quarries) it is necessary to consider Net Recharge in terms of volumes of leachate generated; the Hydraulic Conductivity in relation to migration rates; and Aquifer Media for possible attenuation of contaminants, dispersion, dilution, and routing. Again, surface characteristics are of lesser importance; Topography, Soil Media, and Impact of Vadose Zone.

Thus, man's activities and the intensity of these activities present many potential contamination problems. The impact of these activities is discussed in Section 5, Impact—Risk Factors. Activities are not directly involved in the determination of the DRASTIC Index, but their impact is always of serious concern. These activities may be categorized according to their relative position with respect to the ground water; Table 11 represents a comprehensive list of activities that are potential sources of contamination and their respective modes of emplacement. Each of these sources will be discussed individually in relation to their effects and potential for ground-water contamination.

Ground Water Quality Problems that Originate on the Land Surface

Land Disposal

One of the major causes of ground-water pollution is the disposal of solid or liquid waste materials directly onto the land surface in either individual deposits or spread over the land. Any soluble products present in the waste can be transported into the ground water either with the liquid portion of the wastes or as a consequence of precipitation. Land disposal practices include the application of sewage sludge, manure, garbage, industrial wastes, waste tailings, and spoil piles. These activities are capable of producing a wide variety of contaminants, including organic chemicals, inorganic chemicals, and reactive ions.

Stockpiles and Mine Tailings

The presence of material stockpiles, and mine tailings and spoils, pose a potential source of ground-water contamination. An estimated 20 percent of total production materials are stored in stockpiles of varying sizes (OTA, 1984). Materials that are commonly stockpiled that may affect ground-water quality include salt, coal, various metallic ores (e.g. copper, uranium, titanium, vanadium, silver, lead, zinc), phosphates, and gypsum. These stockpiles are usually exposed to precipitation such that the precipitation will dissolve or react with other constituents to produce leachate that can percolate into the ground-water system. The stockpiling of salt in snow-belt states provides a prime example of how stockpiling can have a dramatic impact on ground-water quality. The salt, if uncovered, is easily dissolved by precipitation and either infiltrates to the subsurface or runs off into streams (Lehr, et al., 1976).

The stockpiling of coal and associated mining processes can also degrade the quality of the ground water. Most coal that is mined is associated with pyrite, an iron sulfide. Contact with water tends to break the pyrite down into iron hydroxide and sulfuric acid. These constituents increase the iron and sulfate levels if they reach the ground water (Bouwer, 1978).

Spoil piles are generally disturbed soils and overburden from surface mining, or waste rock from underground mining. Tailings are the solid wastes from the on-site operations of cleaning and extracting the ores. Both types of waste are usually stored on the land surface. Water moving through the waste piles will mobilize many hazardous constituents, depending on the materials. Because of their quantity, distribution, and nature of their contents, spoil piles and tailings are major potential sources of ground-water contamination. Hazardous constituents from this source can include lead, zinc, copper, and other heavy metals, arsenic, sulfuric acid, and radioactive elements such as uranium and thorium (Bouwer, 1978; Todd, 1980). The impact of spoil piles and tailings is dependent on the location, size, and composition of the tailings and spoils, the climate (amounts of precipitation), the hydrogeologic setting, and type of control and containment of the wastes.

Disposal of Sewage and Water Treatment Plant Sludge

The land application of treated waste waters and sewage sludge from municipal and industrial sources is often used as an alternative to more expensive disposal processes. The waste waters are typically applied as spray irrigation by various land treatment systems (Bouwer, 1978; Todd, 1980). Land treatment of waste waters is generally capable of removing nitrogen, phosphorous, organic waste matter, bacteria, and viruses. Sludge wastes may be applied as compost to agricultural and forested land, disposed of in landfills or applied in land reclamation projects (OTA, 1984). Municipal sludges typically contain nitrogen, phosphorous, organic material, bacteria, viruses, and metals. The presence of undesirable constituents may limit the land application of sludges and waste waters. Some hazardous materials may be preferentially sorbed by plants or infiltrate into ground-water resources. However, studies have shown that high-rate land treatment systems are capable of removing infectious bacteria and viruses through the mechanisms of sorption, mechanical filtration, or die-off (Freeze and Cherry, 1979; Bouwer, 1978). The rate and duration of sludge and waste water application is dependent on the soil and waste characteristics, the length of the application, the nutrient uptake of the cover crop, and the climate.

Salt Spreading

The increased usage of de-icing salts rather than sand and other abrasives in snow belt states provides an actual and a potential source of ground-water contamination. The salts consist of commercial rock and marine salt, with ferric ferrocyanide and sodium ferrocyanide added to reduce caking (Bouwer, 1978). The sodium ferrocyanide is soluble and can increase the concentrations of cyanide present in ground water above safe drinking water levels. In addition, chromate and phosphate may be added to decrease the corrosiveness of the salt; these also affect ground-water quality. Many cases of ground-water contamination have been cited from road salt applications (Bouwer, 1978). Contamination may be minimized by designing roads to reduce de-icing requirements, better collection and disposal of salty run-off, protective salt storage, and use of alternate de-icing materials.

Animal Feed Lots

Accumulations of animal wastes at feed lots can contaminate ground water by infiltration of leachate or surface runoff. The primary contaminant of the leachate is organic, or ammonium, nitrogen which is converted to nitrate in the vadose zone. Additional hazardous constituents include bacteria, viruses, and phosphates (Bouwer, 1978; OTA, 1984). Animal feedlots are most concentrated in the corn belt and High Plains regions. Ground-water contamination tends to be more severe at feed lots underlain by coarse-textured soils with shallow water tables than by fine-textured soils with deeper water tables. These wastes may be controlled by applying animal waste slurries intermittently to maintain aerobic conditions in the upper soil. The nitrogen will be converted to nitrate in the upper soil layer and then be denitrified, or converted to nitrogen gas and water in the deeper anaerobic soil layers.

Fertilizers and Pesticides

Modern agricultural practices employ the extensive use of fertilizers and pesticides to obtain high crop yields. The primary fertilizers are compounds of nitrogen, phosphorous, and potassium. Excess potassium and phosphorous are readily sorbed onto soil particles and seldom constitute a contamination problem. Crop uptake of fertilizer nitrogen varies from about 40 to 80 percent of the amount applied (Bouwer, 1980). The remainder is either volatized and returned to the atmosphere through denitrification, or percolates downward as nitrate to contaminate ground water. Efficient application of fertilizer, particularly at peak requirements during growth cycles, minimizes nitrate contamination (OTA, 1984). Unfortunately, most farmers apply enough fertilizer for the entire growing season prior to planting, thus increasing the potential for nitrate contamination.

Pesticides are chemicals used for the control of insects, fungi, or other undesirable organisms and weeds. Agricultural activities account for between 69 and 72 percent of pesticide use; government agencies and industries use 21 percent; home and garden uses constitute the remainder. Agricultural applications of pesticides have resulted in ground-water contamination in at least 18 states involving a variety of pesticides (OTA, 1984; Cohen et al., 1984). Contamination can occur from common-use practices, spills, disposal of excess pesticides, and leakage from storage containers. Applications of pesticides by airplanes pose a significant problem due to the large quantities applied and indiscriminant application.

The movement and attenuation of pesticides in the soil and ground water is dependent on several parameters including water solubility, vapor pressure, speciation, hydrolysis half-life, photolysis half-life, soil and water sorption properties, and climate (OTA, 1984; Cohen, et al., 1984). The primary parameters that account for pesticide attenuation are sorption, volatilization, biodegradation, and solubility. Those pesticides that are relatively refractory tend to be the least soluble and most resistant to biodegradation and hydrolysis (Tabak et al., 1984; Cohen et al., 1984). The most toxic and refractory pesticides are the chlorinated hydrocarbons such as DDT, lindane, endrin, DDE, and chlordane. The organic phosphate pesticides such as malathion and parathion are less toxic than the chlorinated hydrocarbons and more easily attenuated. The least toxic pesticides are the carbamates such as sevin and captan; these are easily biodegraded by common soil organisms.

Accidental Spills of Hazardous Materials

A wide variety of hazardous materials are transported throughout the country by truck, rail, and aircraft and transferred at handling facilities such as airports and loading docks. Accidental spills of hazardous materials provide a definite potential for ground-water contamination. The National Academy of Sciences (NAS) estimated that approximately 16,000 spills occur annually, involving a variety of materials such as hydrocarbons (i.e. gasoline, jet fuel), pain products, flammable compounds, various acids, and anhydrous ammonia (OTA, 1984).

There are presently few methods available to quickly and adequately clean up an accidental hazardous waste spill. To make matters worse, a common practice is to spray the spill area with water in order to flush the compounds from the road. The hazardous materials are then washed into drainage ditches or streams from which they have the potential to infiltrate and contaminate the ground water.

The attenuation of hazardous materials is dependent on the site-specific hydrogeochemical characteristics, the chemical(s) spilled, and any remedial actions performed by authorities on the surface materials at the time of the spill. An example of a successful hazardous material spill clean-up is given by Harsh (1975). An acrylonitrile spill (cyanide compound) resulting from a train derailment was quickly remediated by the Ohio Environmental Protection Agency through the application of oxidants that neutralized the hazardous substance.

Particulate Matter from Airborne Sources

A relatively minor, but potential source of ground-water contamination arises from the fallout of particulate matter from the atmosphere. These materials fall to the surface of the earth and are carried as soluble or insoluble products by water to the subsurface. The primary source of atmospheric pollution is automobile emissions and various industrial processes. The major contaminants from these emissions include sulfur and nitrogen compounds, asbestos, and heavy metals (OTA, 1984). The distribution of particulates in the atmosphere and on the surface depends on their size when released, weather patterns, and climate. The attenuation of these pollutants is dependent on the site-specific hydrogeochemical characteristics, the location of pollutant fallout, and the chemical nature of the pollutant itself.

The infiltration of airborne contaminants tends to be higher in heavily industrialized areas (Lehr et al., 1976). Perhaps the major environmental concern today related to airborne contaminants is the effect of acid rain on the surface and subsurface water quality. Several contamination occurrences from airborne pollutants have been cited by EPA, particularly increases in heavy metal concentrations in drinking water due to industrial emissions.

Ground Water Quality Problems that Originate in the Ground Above the Water Table

Leaching Tile Fields, Cesspools, and Privies

A widely distributed source of ground-water pollution is septic tanks and cesspools. These sources discharge large volumes of waste water into the subsurface. A septic tank system consists of a buried tank and leaching tile field designed to collect water suspended wastes, remove settleable solids from liquids by gravity separation, and permit infiltration of the effluent into the soil for general degradation by soil microorganisms. According to OTA (1984), in the mid-1970's there were an estimated 19.5 million domestic on-site disposal systems present in the United States and unknown numbers of commercial and industrial systems.

Septic tank systems are the most frequently reported source of contamination on a local and regional basis (OTA, 1984). The contaminants are primarily derived from human wastes and household cleaners; these include nitrates, chloride, coliform bacteria, viruses, and a variety of organic and inorganic chemicals. The major factors that affect the potential for contamination of ground water by septic systems are the density of systems per area, the hydrogeologic conditions, and the attenuation capacity of the soil through which the effluent percolates. Problems tend to arise from systems that are old and deteriorated and from those systems that are poorly constructed.

Several parameters must be considered in the design and installation of a septic system; these include ground water flow velocity and direction, the storage and carrying capacities of the receiving soil, the sorptive qualities of the soil, the resident microorganism community and the depth to the water table.

Holding Ponds and Lagoons

Holding ponds and lagoons, because of their relative numbers and size, present a significant potential for ground-water contamination. Surface impoundments are used by industries and municipalities for the treatment, retention, and/or disposal of non-hazardous and hazardous liquid wastes. These ponds or lagoons vary in size from two to three feet deep, to more than 30 feet deep, with areas covering from a fraction of an acre to thousands of acres (OTA, 1984). Agricultural, municipal, industrial, and oil and gas production lagoons are typically less than five acres in size. However, industrial impoundments are generally 1000 acres or larger. The size of a mining impoundment depends on the ore and type of mining. The wastewater in industrial surface impoundments may consist of suspended and dissolved solids, pathogenic organisms, oil and grease, detergents, heavy metals, and toxic organic chemicals (Pye et al., 1983).

Holding ponds are supposedly "liquid tight," however, the majority leak large quantities of material, thereby contributing to ground-water pollution. The installation of a double-liner system of plastic and clay has recently become a requirement for these facilities under new RCRA regulations. The presence of a liner combined with a leachate collection drain system will lower the potential of contamination by constituents in the holding pond.

The potential for contamination by a holding pond is dependent on head conditions in the pond, soil permeability, depth to the water table, rates of evaporation and precipitation, geochemical characteristics of the soil (ion exchange and sorption), the chemical composition and amounts of waste, and the capacity for degradation by soil organisms (Pye et al., 1983).

Sanitary Landfills

Sanitary landfills are constructed excavations that are filled with hazardous and non-hazardous waste materials and covered daily by soils. Daily coverage by soils prevents the production of odors, smoke, and the presence of vermin and insects. Precipitation and surface runoff can infiltrate into these landfills producing leachate that can contain soluble hazardous materials. Some hazardous constituents may be attenuated as the leachate filters through the soil zone. However, leachate may still reach the ground water. Landfills are commonly covered with clay and/or soil combinations to minimize the infiltration of water and production of leachate. However, these coverings are not totally impermeable and some moisture penetrates the protective covers.

Approximately 40 percent of the solid hazardous industrial wastes are disposed of in some type of landfill in addition to the large quantities of non-hazardous wastes that are also deposited in these facilities (OTA, 1984). Problems arise with older landfills that are improperly constructed, have failing liners, have accepted unknown types and quantities of wastes, are deteriorating, or have been abandoned. These older and abandoned landfills pose a definite threat to ground water because geologic and hydrogeologic characteristics were not considered in the initial site selection or design.

Ground-water contamination from landfills may be minimized by proper design, construction, operation, and maintenance of a facility (Wilson et al., 1976). Provisions must be made for controlling traffic, unloading and handling different types of wastes, placement of cover materials, testing of wastes for acceptance, and adequate ground-water monitoring to prevent contamination problems.

Waste Disposal in Excavations

The removal of materials such as clay, limestone, and sand and gravels commonly produces pits or excavations that may have been eventually abandoned and used as unregulated waste disposal sites. A wide variety of materials have been emplaced in excavations in unknown quantities. These include garbage, junk automobiles, and liquid wastes such as oil-field brines and spent acids from steel mills. Disposal of unregulated waste poses the threat of ground-water contamination. Often these pits contain some amount of water, evidence that they are hydraulically connected to the water table and possibly deeper aquifers. Leachate from these wastes may therefore have direct access to the ground-water system. This contamination may be avoided through preventative regulations and correct disposal of wastes at a properly designed sanitary landfill or other facility.

Leakage from Underground Storage Tanks

Underground storage tanks are used by industries, commercial establishments, and individuals for storage and treatment of products or raw materials (Wilson et al., 1976). The primary storage materials are hydrocarbon fuels, but many other substances are commonly stored in underground tanks, such as acids, metals, industrial solvents, chemicals, and chemical wastes. The most numerous underground storage tanks are those used for gasoline and fuel oil. Gasoline leakage from leaking tanks has caused severe pollution problems throughout the nation. Because gasoline is less dense than water, it floats on the surface of the ground water and may leak into basements, sewers, wells, and springs. In confined areas, vapors from these leaks, disseminated by ground water, can cause a serious explosion hazard.

Most tanks are composed of either steel or fiberglas. Unprotected steel is subject to rusting or corrosion by various materials. Fiberglas may crack or be slowly dissolved by alcohol blends. Tank age is a principal factor in ground-water contamination; studies have shown that older tanks exhibit a tendency to leak through deterioration of the tank (OTA, 1984). Ground-water pollution is minimized by proper tank design and emplacement, properly placed monitoring wells, frequent inspections, and fluid level monitoring.

Leakage from Underground Pipelines

Pipelines are used to transport, collect, and/or distribute waste and non-waste products. Leaks that occur in pipelines are often difficult to detect and locate. Pipeline leakage occurs due to ruptures, external and internal corrosion, incorrect operation, and defective welds or pipes (Todd, 1980). Wastes transported in pipelines include municipal sewage, petroleum products, brines, ammonia, sulfur, and coal. Interstate pipelines and all spills are regulated by the Department of Transportation. Other collection and distribution pipelines are not regulated other than during initial installation and are not required to report leaks and spills.

Artificial Recharge

Artificial recharge includes a variety of techniques used to increase the amount of water infiltrating into an aquifer. This is achieved through the construction of pits, ponds or wells, or direct land application so that the water will seep into the ground or flow or be pumped directly into the aquifer. Water that is used for artificial recharge commonly consists of storm runoff, irrigation return flows, stream water, cooling water, and treated sewage effluent. The infiltration of this water may directly affect ground-water quality, resulting in subsequent contamination. Recharge is becoming increasingly popular due to the growing demands for water and the need for recycling.

Sumps and Dry Wells

Sumps and dry wells are typically installed to provide drainage in problem areas by collecting runoff or spilled liquids. These liquids are usually channeled into the subsurface where they are transmitted to the ground water. These facilities are especially prone to cause problems if they are located near streams, lakes or ponds, or estuaries where ground-water levels are naturally high.

Graveyards

Leachate from graveyards may cause ground-water pollution, especially if non leak-proof or no caskets were used. The potential for ground-water contamination by graveyards is dependent on several factors, including the characteristics of the soil and depth to the water table (Lehr et al., 1976). Areas that receive high amounts of precipitation and have high water tables may be especially prone to contamination problems. Graveyards also pose a potential contamination problem in areas of hard rock and limestone terrain where soil covers are thin, and in glaciated areas where the glacial sand and gravel lenses are hydraulically interconnected. Few actual cases have been documented and any contamination problems would be highly localized.

Ground Water Quality Problems that Originate in the Ground Below the Water Table

Waste Disposal in Wet Excavations

The removal and mining of various materials often produces excavations and pits that are commonly abandoned after activities cease. These pits often extend below the water table and thereby contain quantities of water. These excavations were used in the past as repositories for both solid and liquid wastes and presently have the potential to produce large quantities of leachate. The leachate produced is in direct hydraulic connection with the shallow ground water and possibly with other deeper aquifers.

Drainage Wells and Canals

In areas that consist of surficial clays and flat-lying land with ponds and marshes that are poorly drained, drainage wells and canals may be constructed. A drainage well is a vertical cased hole in the ground or the bottom of a pond, for example, that allows water to drain into deeper, more permeable materials. Pollution of the recharged surface water may thus contaminate the aquifer.

The construction of extensive channels and channel deepening may have the potential to affect ground-water quality. Deepened channels may affect the ground-water gradient and allow infiltration of surface water or the intrusion of salt or brackish water, thereby causing contamination. Extensive channels in coastal areas have allowed tidal ocean waters to flow inland and affect ground-water quality.

Abandoned or Improperly Constructed Wells

The presence of abandoned wells provides a significant means for ground-water contamination. Wells that have been abandoned commonly provide conduits for the migration of contaminated water. The water may be runoff or surface water that enters through the open conduit, or may be the migration of fluid between an aquifer and a zone of undesirable water quality. When a well is abandoned, the casing is often pulled or is allowed to deteriorate so that casing leaks develop. This readily permits fluids under pressure to migrate, upward or downward, and contaminate the aquifers. Another problem is the migration of saline water into freshwater aquifers. In areas where the hydraulic gradient is toward the freshwater aquifer, abandoned or improperly constructed wells provide a conduit resulting in salt water contamination and intrusion. The migration of contaminated fluids may also occur in areas of deep well disposal injection operations. Contaminated liquids under pressure are able to migrate into other aquifers via uncased wells and deteriorated casings in wells.

Exploratory Wells

Exploratory wells and test holes are frequently drilled to determine the presence of underground mineral resources such as coal, salt, oil, or gas, and as seismic shot holes where an explosive is discharged to produce shock waves for seismic sensors. Where these open holes penetrate more than one aquifer, they permit interaquifer leakage. Thus, brackish water from a saline aquifer could migrate upward or downward to contaminate a fresh water aquifer. These open holes also allow surface waters to enter the hole and migrate into other aquifers.

Water Supply Wells

Improperly constructed water supply wells have the potential to contaminate ground water and produce polluted water. Large diameter dug wells are particularly prone to contamination from surface runoff if not properly protected during and following construction. Improper grouting of the annular space around the casing may allow surface contaminants to enter the aquifer. Drainage from animal feedlots, barnyards, septic tanks, or cesspool effluent may also contaminate improperly constructed wells. Proper training and licensing of well drillers and the implementation of water well construction standards minimizes pollution problems of this nature.

Waste Disposal Wells

Wells are used to inject or discharge either hazardous or non-hazardous waste into a permeable geologic unit beneath the surface. Industrial injection wells may range in depth from a few tens of feet to several thousand feet. The EPA estimates that at least 21,000 wells in the United States require some type of corrective action (OTA, 1984). Contamination from injection wells can occur in a number of ways, including: (1) faulty well construction, (2) the migration of pressurized fluids into nearby wells and aquifers, (3) the forcing upward of pressurized fluids into faults or fractures in confining beds, (4) injection into or above usable aquifers, (5) the migration of contaminated fluids into other hydraulically connected aquifers used as drinking water supplies, and (6) faulty well sealing that allows the entrance of surface runoff into the well. Since the implementation of the Federal Underground Injection Control Act (UIC), the installation and operation of underground injection wells is regulated.

Mines

Excavation and operation of both surface and underground mines can disrupt the natural continuity of aquifers and introduce fractures and pressure changes which affect the ground-water flow. This allows water to migrate through the fractured overburden into other aquifers and/or to mix with mine spoils and tailings. Often mines will intersect the water table, or various aquifers, necessitating dewatering of the mine by pumping large quantities of water to the surface. This water may be contaminated and pollute aquifers, streams, or surface bodies of water into which it infiltrates or drains. Dewatering of mines may also cause salt water intrusion by lowering the fresh water table. Underground mining tends to introduce water and oxygen into the subsurface which results in the oxidation of pyrite and the subsequent formation of acidic mine drainage (Pye et al., 1983). Acid mine drainage is a mixture of iron salts, other salts, and sulfuric acid, and may substantially contribute to ground-water contamination. In order to protect the surface and ground-water resources, mining activities must be carefully designed, operated, and regulated from their planning phase to final reclamation of the land.

Salt Water Intrusion

Withdrawals of ground water in excess of recharge capabilities often results in contamination of an aquifer by salt water intrusion. This problem is especially prevalent in densely populated coastal areas where large quantities of fresh water are pumped daily. Overdrafting disrupts the natural hydrologic processes and affects subsequent impacts on aquifers and ground-water quality. Increased pumpage of fresh water will tend to lower the water table in the vicinity of the well, causing changes in the hydraulic gradient. This allows intrusion of salt water along the hydraulic slope into a pumping well (Freeze and Cherry, 1979). Land subsidence may also occur with increased pumping and reduction of the water table. In some coastal areas, injection of freshwater into aquifers is used to prevent salt-water intrusion.

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