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Handbook

Ground Water

Volume I: Ground Water and Contamination

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U.S. Environmental Protection Agency
Office of Research and Development

Center for Environmental Research Information
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NOTICE

This document has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This document is not intended to be a guidance or support document for specific regulatory program. Guidance documents are available from EPA and must be consulted to address specific regulatory issues.

Contents

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Volume I, Ground Water and Contamination, will be followed by Volume II, Methodology. Although extensively revised, Volume I was obtained from previous publlications, "Handbook: Ground Water" (EPA/625/6-87/016) and "Protection of Public Water Supplies from Ground-Water Contamination" (EPA/625/4-85/016).

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Preface

The subsurface environment of ground water is characterized by a complex interplay of physical, geochemical and biological forces that govern the release, transport and fate of a variety of chemical substances. There are literally as many varied hydrogeologic settings as there are types and numbers of contaminant sources. In situations where ground-water investigations are most necessary, there are frequently many variables of land and ground-water use and contaminant source characteristics which cannot be fully characterized.

The impact of natural ground-water recharge and discharge processes on distributions of chemical constituents is understood for only a few types of chemical species. Also, these processes may be modified by both natural phenomena and man's activities so as to further complicate apparent spatial or temporal trends in water quality. Since so many climatic, demographic and hydrogeologic factors may vary from place to place, or even small areas within specific sites, there can be no single "standard" approach for assessing and protecting the quality of ground water that will be applicable in all cases.

Despite these uncertainties, investigations are under way and they are used as a basis for making decisions about the need for, and usefulness of, alternative corrective and preventive actions. Decision makers, therefore, need some assurance that elements of uncertainty are minimized and that hydrogeologic investigations provide reliable results.

A purpose of this document is to discuss measures that can be taken to ensure that uncertainties do not undermine our ability to make reliable predictions about the response of contamination to various corrective or preventive measures.

EPA conducts considerable research in ground water to support its regulatory needs. In recent years, scientific knowledge about ground-water systems has been increasing rapidly. Researchers in the Office of Research and Development have made improvements in technology for assessing the subsurface, in adapting techniques from other disciplines to successfully identify specific contaminants in ground water, in assessing the behavior of certain chemicals in some geologic materials and in advancing the state-of-the-art of remedial technologies.

An important part of EPA's ground-water research program is to transmit research information to decision makers, field managers and the scientific community. This publication has been developed to assist that effort and, additionally, to help satisfy an immediate Agency need to promote the transfer of technology that is applicable to ground-water contamination control and prevention.

The need exists for a resource document that brings together available technical information in a form convenient for ground-water personnel within EPA and state and local governments on whom EPA ultimately depends for proper ground-water management. The information contained in this handbook is intended to meet that need. It is applicable to many programs that deal with the ground-water resource. However, it is not intended as a guidance or support document for a specific regulatory program.

GUIDANCE DOCUMENTS ARE AVAILABLE FROM EPA AND MUST BE CONSULTED TO ADDRESS SPECIFIC REGULATORY ISSUES.

Chapter 1

BASIC GEOLOGY

Introduction

Geology, the study of the earth, includes the investigation of earth materials, the processes that act on these materials, the products that are formed, the history of the earth, and the origin and development of life forms. There are several subfields of geology. Physical geology deals with all aspects of the earth and includes most earth science specialities. Historical geology is the study of the origin of the earth, continents and ocean basins, and life forms, while economic geology is an applied approach involved in the search and exploitation of mineral resources, such as metallic ores, fuels, and water. Structural geology deals with the various structures of the earth and the forces that produce them. Geophysics is the examination of the physical properties of the earth and includes the study of earthquakes and methods to evaluate the subsurface.

From the perspective of ground water, all of the subfields of geology are used, some more than others. Probably the most difficult concept to comprehend by individuals with little or no geological training is the complexity of the subsurface, which is hidden from view and, at least presently, cannot be adequately sampled. In geologic or hydrogeologic studies, it is best to always keep in mind a fundamental principle of geology, that is, the present is the key to the past. This means that the processes that are occurring today are the same processes that occurred throughout the geologic past—only the magnitude has changed from one time to the next.

Consider, for example, the channel and flood plain of a modern day river or stream. The watercourse constantly meanders from one side of the flood plain to another, eroding the banks and carrying the sediments farther downstream. The channel changes in size and position, giving rise to deposits of differing grain size and, perhaps, composition. The changes may be abrupt or gradual, both vertically and horizontally, as is evident from an examination of the walls of a gravel pit or the bluffs along a river. Because of the dynamic nature of streams and deltas, one will find a geologic situation that is perplexing, not only to the individual involved in a ground-water investigation, but to the geologist as well. Each change in grain size will cause a difference in permeability and ground-water velocity, while changes in mineral composition can lead to variances in water quality. At the other end of the depositional spectrum are deposits collected in lakes, seas, and the oceans, which are likely to be much more widespread and uniform in thickness, grain size, and composition.

As one walks from the sandy beach of a lake into the water, the sediments become finer and more widely distributed as the action of waves and currents sort the material brought into the lake by streams. Farther from shore, the bottom of the lake may consist of mud, which is a mixture of silt, clay, and organic matter. In some situations the earthy mud grades laterally into a lime ooze or mud. In geologic time these sediments become lithified or changed into rock...the sand to sandstone, the mud to shale, and the limy mud to limestone. It is important to note, however, that the sand, mud, and lime were all deposited at the same time, although with lithification each sediment type produced a different sedimentary rock.

Minerals

The earth, some 7,926 miles in diameter at the equator, consists of a core, mantle, and crust, which have been defined by the analysis of seismic or earthquake waves. Only a thin layer of the crust has been examined by humans. It consists of a variety of rocks, each of which is made up of one or more minerals.

Most minerals contain two or more elements, but of all of the elements known, only eight account for nearly 98 percent of the rocks and minerals:

Oxygen 46%
Silicon 27.72%
Aluminum 8.13%
Iron 5%
Calcium 3.63%
Sodium 2.83%
Potassium 2.59%
Magnesium 2.09%

Without detailed study, it is usually difficult to distinguish one mineral from another, except for a few common varieties, such as quartz, pyrite, mica, and some gemstones. On the other hand, it is important to have at least a general understanding of mineralogy because it is the mineral make-up of rocks that, to a large extent, controls the type of water that a rock will contain under natural conditions and the way it will react to contaminants or naturally occurring substances.

The most common rock-forming minerals are relatively few and deserve at least a mention. They can be divided into three broad groups: (1) the carbonates, sulfates, and oxides, (2) the rock-forming silicate minerals, and (3) the common ore minerals.

Carbonates, Sulfates, and Oxides
Calcite, a calcium carbonate ($CaCO_3$), is the major mineral in limestone. It is quite soluble, which accounts for its usual presence in water. The most common mineral is quartz. It is silicon dioxide (SiO_2), hard, and resistant to both chemical and mechanical weathering. In sedimentary rocks it generally occurs as sand-size grains (sandstone) or even finer, such as silt or clay size, and it may also appear as a cement. Because of the low solubility of silicon, silica generally appears in concentrations less than 25 mg/L in water. Limonite is actually a group name for the hydrated ferric oxide minerals ($Fe_2O_3H_2O$), which occur so commonly in many types of rocks. Limonite is generally rusty or blackish with a dull, earthy luster and a yellow-brown streak. It is a common weathering product of other iron minerals. Because limonite and other iron-bearing minerals are nearly universal, dissolved iron is a very common constituent in water and causes staining of clothing and plumbing fixtures. Gypsum, a hydrated calcium sulfate ($CaSO_4 \cdot 2H_2O$), occurs as a sedimentary evaporite deposit and as crystals in shale and some clay deposits. Quite soluble, it is the major source of sulfate in ground water.

Rock-Forming Silicates
The most common rock-forming silicate minerals include the feldspars, micas, pyroxenes, amphiboles, and olivine. Except in certain igneous and metamorphic rocks, these minerals are quite small and commonly require a microscope for identification. The feldspars are alumino-silicates of potassium or sodium and calcium. Most of the minerals in this group are white, gray, or pink. Upon weathering they turn to clay and release the remaining chemical elements to water. The micas, called muscovite and biotite, are platy alumino-silicate minerals that are common and easily recognized in igneous, metamorphic, and sedimentary rocks. The pyroxenes, a group of silicates of calcium, magnesium, and iron, as well as the amphiboles, which are complex hydrated silicates of calcium, magnesium, iron, and aluminum, are common in most igneous and metamorphic rocks. They appear as small, dark crystals of accessory minerals. Olivine, a magnesium-iron silicate, is generally green or yellow and is common in certain igneous and metamorphic rocks. None of the rock-forming silicate minerals have a major impact on water quality in most situations.

Next to organic matter, clay minerals are the most chemically active materials in soil and unconsolidated materials. Both consolidated rocks and unconsolidated sediments that have a high clay mineral content tend to have low permeabilities and, consequently, water movement through them is very slow. The two broad groups of clay minerals commonly recognized are the silicate clays and the hydrous oxide clays. Silicate clays form from the weathering of primary silicate minerals, such as feldspars and olivine. They have a sheet-like lattice structure and a strong adsorptive capacity. Silicate clays are classified according to different stacking arrangements of the lattice layers and their tendency to expand in water. The stacking type strongly affects certain properties of clays, including (l) surface area, (2) the tendency to swell during hydration, and (3) cation exchange capacity (CEC), which is a quantitative measure of the ability of a mineral surface to adsorb ions.

Table1-1 summarizes some properties of silicate clay minerals, which are listed from the most reactive (montmorillonite and vermiculite) to least reactive (kaolinite). The montmorillonite group is most sensitive to swelling and has a high CEC. The structure in kaolinite results in both a low surface area and CEC. Illite and chlorite have intermediate surface areas, CEC, and sensitivities to swelling. Clay minerals in sedimentary rocks are usually mixtures of different groups. In addition, mixed-layer clay minerals can form and these have properties and compositions that are intermediate between two well-defined clay types (e.g., chlorite-illite, illite-montmorillonite). Hydrous oxide clays, which are less well understood than silicate clays, are oxides of iron, magnesium, and aluminum that are associated with water molecules. Compared to silicate clays, CEC is lower in hydrous oxide clays.

		Type of Clay[a]			
Property	Montmorillonite (Smetite)	Verriculite	Illite	Chlorite	Kaolinite
Lattice type[c]	2:1	2:1	2:1	2:2	1:1
Expanding?	Yes	Slightly	No	No	No
Specific surface (m^2/g)	700-800	700-800	65-120	25-40	7-30
External surface	High	High	Medium	Medium	Low
Internal surface	Very High	High	Medium	Medium	None
Swelling capacity	High	Med-High	Medium	Low	Low
Cation exchange capacity (meq/100g)	80-150	100-150+	10-40	10-40	3-15
Other similar Clays	Beidellite Nontrorite Saporite Bentonite[d]				Halloysite Anauxite Dickit

[a] Clays are arranged from most reactive (montmorillonite) to least reactive (kaolinite).

[b] The term smectite is now used to refer to the montmorillonite group of clays (Soil Science Society of America, 1987)

[c] Tetrahedral:octahedral layers.

[d] Bentonite is a clay formed from weathering of volcanic ash and is made up mostly of montmorillonite and beidellite.

[e] Upper range occurs with smaller particle size.

Sources: Adapted from Grim (1968), Brady (1974), and Ahlrichs (1972).

Table 1-1. Important Characteristics of Silicate Clay Minerals

Ores

The three most common ore minerals are galena, sphalerite, and pyrite. Galena, a lead sulfide (PbS), is heavy, brittle, and breaks into cubes. Sphalerite is a zinc sulfide (ZnS) mineral that is brownish, yellowish, or black. It ordinarily occurs with galena and is a major ore of zinc. The iron sulfide pyrite (FeS), which is also called fool's gold, is common in nearly all types of rocks. It is the weathering of this mineral that leads to acid-mine drainage, which is common in many coal fields and metal sulfide mining regions.

Rocks, Their Origin and Properties

Three types of rock comprise the crust of the earth. Igneous rocks solidified from molten material either within the earth (intrusive) or on or near the surface (extrusive). Metamorphic rocks were originally igneous or sedimentary rocks that were modified by temperature, pressure, and chemically active fluids. Sedimentary rocks are the result of the weathering of preexisting rocks, erosion, and deposition. Geologists have developed elaborate systems of nomenclature and classification of rocks, but these are of little value in hydrogeologic studies and, therefore, only the most basic descriptions will be presented.

Igneous Rocks

Igneous rocks are classified on the basis of their composition and grain size. Most consist of feldspar and a variety of dark minerals; several others also contain quartz. If the parent molten material cools slowly deep below the surface, minerals will have an opportunity to grow and the rock will be coarse grained. Magma that cools rapidly, such as that derived from volcanic activity, is so fine grained that individual minerals generally cannot be seen even with a hand lens. In some cases the molten material began to cool slowly, allowing some minerals to grow, and then the rate increased dramatically so that the remainder formed a fine groundmass. This texture, consisting of large crystals in a fine-grained matrix, is called porphyritic.

Intrusive igneous rocks can only be seen where they have been exposed by erosion. They are concordant if they more or less parallel the bedding of the enclosing rocks and discordant if they cut across the bedding. The largest discordant igneous masses are called batholiths and they occur in the eroded centers of many ancient mountains. Their dimensions are in the range of tens of miles. Batholiths usually consist largely of granite, which is surrounded by metamorphic rocks.

Discordant igneous rocks also include dikes that range in width from a few inches to thousands of feet. Many are several miles long. Sills are concordant bodies that have invaded sedimentary rocks along bedding planes. They are relatively thin. Both sills and dikes tend to cool quite rapidly and, as a result, are fine grained.

Extrusive rocks include lava flows or other types associated with volcanic activity, such as the glassy rock, pumice, and the consolidated ash called tuff. These are fine grained or even glassy.

With some exceptions, igneous rocks are dense and have very little porosity or permeability. Most, however, are fractured to some degree and can store and transmit a modest amount of water. Some lava flows are notable exceptions because they contain large diameter tubes or a permeable zone at the top of the flow where gas bubbles migrated to the surface before the rock solidified. These rocks are called scoria.

Metamorphic Rocks

Metamorphism is a process that changes preexisting rocks into new forms because of increases in temperature, pressure, and chemically active fluids. Metamorphism may affect igneous, sedimentary, or other metamorphic rocks. The changes brought about include the formation of new minerals, increase in grain size, and modification of rock structure or texture, all of which depend on the original rock's composition and the intensity of the metamorphism.

Some of the most obvious changes are in texture, which serves as a means of classifying metamorphic rocks into two broad groups, the foliated and non-foliated rocks. Foliated metamorphic rocks typify regions that have undergone severe deformation, such as mountain ranges. Shale, which consists mainly of silt and clay, is transformed into slate by the change of clay to mica. Mica, being a platy mineral, grows with its long axis perpendicular to the principal direction of stress, forming a preferred orientation. This orientation, such as the development of cleavage in slate, may differ greatly from the original bedding.

With increasing degrees of metamorphism, the grains of mica grow to a larger size so that the rock has a distinct foliation, which is characteristic of the metamorphic rock, schist. At even higher grades of metamorphism, the mica may be transformed to a much coarser-grained feldspar, producing the strongly banded texture of gneiss.

Non-foliated rocks include the hornfels and another group formed from rocks that consist mainly of a single mineral. The hornfels occur around an intrusive body and were changed by "baking" during intrusion. The second group includes marble and quartzite, as well as several other forms. Marble is metamorphosed limestone and quartzite is metamorphosed quartz sandstone.

There are many different types of metamorphic rocks, but from a hydrogeologic viewpoint they normally neither store nor transmit much water and are of only minor importance as aquifers. Their primary permeability is notably small, if it exists at all, and fluids are forced to migrate through secondary openings, such as faults, joints, or other types of fractures.

Sedimentary Rocks

Sedimentary rocks are deposited, either in a body of water or on the land, by running water, by wind, and by glaciers. Each depositional agent leaves a characteristic stamp on the material it deposits. The sediments carried by these agents were first derived by the weathering and erosion of preexisting rocks. The most common sedimentary rocks are shale, siltstone, sandstone, limestone, and glacial till. The change from a loose, unconsolidated sediment to a rock is the process of lithification. Although sedimentary rocks appear to be the dominant type, in reality they make up but a small percentage of the earth. They do, however, form a thin crust over much of the earth's surface, are the type most readily evident, and serve as the primary source of ground water.

The major characteristics of sedimentary rocks are sorting, rounding, and stratification. A sediment is well sorted if the grains are nearly all the same size. Wind is the most effective agent of sorting and this is followed by water. Glacial till is unsorted and consists of a wide mixture of material that ranges from large boulders to clay.

While being transported, sedimentary material loses its sharp, angular configuration as it develops some degree of rounding. The amount of rounding depends on the original shape, composition, transporting medium, and the distance traveled.

Sorting and rounding are important features of both consolidated and unconsolidated material because they have a major control on permeability and porosity. The greater the degree of sorting and rounding the higher will be the water-transmitting and storage properties. This is why a deposit of sand, in contrast to glacial till, can be such a productive aquifer.

Most sedimentary rocks are deposited in a sequence of layers or strata. Each layer or stratum is separated by a bedding plane, which probably reflects variations in sediment supply or some type of short-term erosion. Commonly bedding planes represent changes in grain size. Stratification provides many clues in our attempt to unravel geologic history. The correlation of strata between wells or outcrops is called stratigraphy.

Sedimentary rocks are classified on the basis of texture (grain size and shape) and composition. Clastic rocks consist of particles of broken or worn material and include shale, siltstone, sandstone, and conglomerate. These rocks are lithified by compaction, in the case of shale, and by cementation. The most common cements are clay, calcite, quartz, and limonite. The last three, carried by ground water, precipitate in the unconsolidated material under specific geochemical conditions.

The organic or chemical sedimentary rocks consist of strata formed from or by organisms and by chemical precipitates from sea water or other solutions. Most have a crystalline texture. Some consist of well preserved organic remains, such as reef deposits and coal seams. Chemical sediments include, in addition to some limestones, the evaporites, such as halite (sodium chloride), gypsum, and anhydrite. Anhydrite is an anhydrous calcium sulfate.

Geologists also have developed an elaborate classification of sedimentary rocks, which is of little importance to the purpose of this introduction. In fact, most sedimentary rocks are mixtures of clastic debris, organic material, and chemical precipitates. One should keep in mind not the various classifications, but rather the texture, composition, and other features that can be used to understand the origin and history of the rock.

The term texture has different meanings in geology and soil science. In soil science it is simply the relative proportions of clay-, silt-, and sand-sized particles in soil or unconsolidated material. The term fabric applies to the total of all physical features of a rock or soil that can be observed. Soil fabric analysis involves the study of distinctive physical features resulting from soil-forming processes, which also strongly influence the location and rate of water movement in soil.

A variety of scales are available for the classification of materials based on particle-size distribution. In geology, the Wentworth-Udden scale is most widely used: boulder (>256 mm), cobble (64-256 mm), pebble (4-64 mm), granule or gravel (2-4 mm), sand (1/16-2 mm), silt (1/256-1/16 mm), and clay (<1/256 mm). The U.S. Department of Agriculture (USDA) soil textural classification system is most widely used by soil scientists, and engineers usually use the Unified soil classification system. The hydrologic properties of soils are strongly related to particle-size distribution.

Weathering

Generally speaking, a rock is stable only in the environment in which it was formed. Once removed from that environment, it begins to change, rapidly in a few cases, but more often slowly, by weathering. The two major processes of weathering are mechanical and chemical, but they usually proceed in concert.

Mechanical Weathering

Mechanical weathering is the physical breakdown of rocks and minerals. Some is the result of fracturing due to the volumetric increase when water in a crack turns to ice, some is the result of abrasion during transport by water, ice, or wind, and a large part is the result of gravity causing rocks to fall and shatter. Mechanical weathering alone only reduces the size of the rock; its chemical composition is not changed. The weathered material formed ranges in size from boulders to silt.

Chemical Weathering

Chemical weathering, on the other hand, is an actual change in composition as minerals are modified from one type to another. Many, if not most of the changes are accompanied by a volumetric increase or decrease, which in itself further promotes additional chemical weathering. The rate depends on temperature, surface area, and available water.

The major reactions involved in chemical weathering are oxidation, hydrolysis, and carbonation. Oxidation is a reaction with oxygen to form an oxide, hydrolysis is reaction with water, and carbonation is a reaction with CO_2 to form a carbonate. In these reactions the total volume increases and, since chemical weathering is most effective on grain surfaces, disintegration of a rock occurs.

Quartz, whether vein deposits or individual grains, undergoes practically no chemical weathering; the end product is quartz sand. Some of the feldspars weather to clay and release calcium, sodium, silica, and many other elements that are transported in water. The iron-bearing minerals provide, in addition to iron and magnesium, weathering products that are similar to the feldspars.

Basic Soil Concepts

Although the term soil is often loosely used to refer to any unconsolidated material, soil scientists distinguish it from other unconsolidated geologic materials by observable features, such as accumulation of organic matter, formation of soil structure, and leaching, that result from soil-forming processes.

The soil at a particular location is the result of the interaction of five factors: (l) parent material, (2) topography, (3) climate, (4) biota, and (5) time. The interaction of these factors results in the formation of a soil profile, the description of which forms the basis for classifying a soil. Specific soil-forming processes that influence soil profile development include (l) organic matter accumulation; (2) weathering of minerals to clays; (3) the depletion of clay and other sesquioxide minerals from upper horizons (eluviation), with subsequent enrichment in lower horizon (illuviation); (4) leaching or accumulation of soluble salts; (5) the formation of soil structure by the aggregation of soil particles into larger units called peds; and (6) the formation of slowly permeable layers called fragipans.

Perhaps the most distinctive features of a soil profile are its major horizons. The O horizon, if present, is a layer of partially decomposed organic material. The A horizon, which lies at the surface or near surface, is a mineral horizon characterized by maximum accumulation of organic matter; it usually has a distinctly darker color than lower horizons. The B horizon, the zone of most active weathering, is commonly enriched in clays, and has a well-defined soil structure. The C horizon is unconsolidated material that has experienced little or no weathering. The R horizon is solid rock.

Soil physical properties, such as texture, structure, and pore size distribution, are the major determinants in water movement in soil. Depending on the specific soil, water movement may be enhanced or retarded compared to unweathered geologic materials. Organic matter enhances water-holding capacity and infiltration. The formation of soil structure also enhances permeability, particularly in clayey soils. On the other hand, the formation of restrictive layers, such as fragipans, may substantially reduce infiltration compared to unweathered materials. Micromorphological and general fabric analysis of soil is used infrequently in the study of ground-water contamination, more because of unfamiliarity with the methods than their lack of value.

Minerals in the soil are the chemical signature of the bedrock from which they originated. Rainfall and temperature are two significant factors that dictate the rate and extent to which mineral solids in the soil react with water. Organic matter and clay content are major parameters of importance in studying the transport and fate of contaminants in soil.

Erosion and Deposition

Once a rock begins to weather, the by-products await erosion or transportation, which must be followed by deposition. The major agents involved in this part of the rock cycle are running water, wind, and glacial ice.

Waterborne Deposits

Mass wasting is the downslope movement of large amounts of detrital material by gravity. Through this process, sediments are made available to streams that carry them away to a temporary or permanent site of deposition. During transportation some sorting occurs and the finer silt and clay are carried farther downstream. The streams, constantly filling, eroding, and widening their channels, leave materials in their valleys that indicate much of the history of the region. Stream valley deposits, called alluvium, are shown on geologic maps by the symbol Qal, meaning Quaternary age alluvium. Alluvial deposits are distinct, but highly variable in grain size, composition, and thickness. Where they consist of glacially derived sand and gravel, called outwash, they form some of the most productive water-bearing units in the world.

Sediments, either clastic or chemical/organic, transported to past and present seas and ocean basins spread out to form, after lithification, extensive formations of sandstone, siltstone, shale, and limestone. In the geologic past, these marine deposits covered vast areas and when uplifted they formed the land surface, where they again began to weather in anticipation of the next trip to the ocean.

The major features of marine sedimentary rocks are their widespread occurrence and rather uniform thickness and composition, although extreme changes exist in many places. If not disturbed by some type of earth movement, they are stratified and horizontal. Furthermore, each lithologic type is unique relative to adjacent units. The bedding planes or contacts that divide them represent distinct differences in texture or composition. From a hydrologic perspective, differences in texture from one rock type to another produce boundaries that strongly influence ground-water flow. Consequently, ground water tends to flow parallel to these boundaries, that is, within a particular geologic formation, rather than across them.

Windborne Deposits

Wind-laid or eolian deposits are relatively rare in the geologic record. The massively cross-bedded sandstone of the Navajo Sandstone in Utah's Zion National Park and surrounding areas is a classic example in the United States. Other deposits are more or less local and represent dunes formed along beaches of large water bodies or streams. Their major characteristic is the high degree of sorting. Dunes, being relatively free of silt and clay, are very permeable and porous, unless the openings have been filled by cement. They allow rapid infiltration of water and can form major water-bearing units, if the topographic and geologic conditions are such that the water does not rapidly drain.

Another wind-deposited sediment is loess, which consists largely of silt. It lacks bedding but is typified by vertical jointing. The silt is transported by wind from deserts, flood plains, and glacial deposits. Loess weathers to a fertile soil and is very porous. It is common along the major rivers in the glaciated parts of the United States and in China, parts of Europe, and adjacent to deserts and deposits of glacial outwash.

Glacial Deposits

Glaciers erode, transport, and deposit sediments that range from clay to huge boulders. They subdue the land surface over which they flow and bury former river systems. The areas covered by glaciers during the last Ice Age in the United States are described in Chapter 2, but the deposits extend far beyond the former margins of the ice. The two major types of glaciers include valley or mountain glaciers and the far more extensive continental glaciers. The deposits they leave are similar and differ, for the most part, only in scale.

As a glacier slowly passes over the land surface, it incorporates material from the underlying rocks into the ice mass, only to deposit that material elsewhere when the ice melts. During this process, it modifies the land surface, both through erosion and deposition. The debris associated with glacial activity is collectively termed glacial drift. Unstratified drift, usually deposited directly by the ice, is glacial till, a heterogeneous mixture of boulders, gravel, sand, silt, and clay. Glacial debris reworked by streams and in lakes is stratified drift. Although stratified drift may range widely in grain size, the sorting far surpasses that of glacial till. Glacial lake clays are particularly well sorted.

Glacial geologists usually map not on the basis of texture, but rather the type of landform that was developed, such as moraines, outwash, drumlins, and so on. The various kinds of moraines and associated landforms are composed largely of unstratified drift with incorporated layers of sand and gravel. Stratified drift is found along existing or former stream valleys or lakes that were either in the glacier or extended downgradient from it. Meltwater stream deposits are mixtures of sand and gravel. In places, some have coalesced to develop extensive outwash plains.

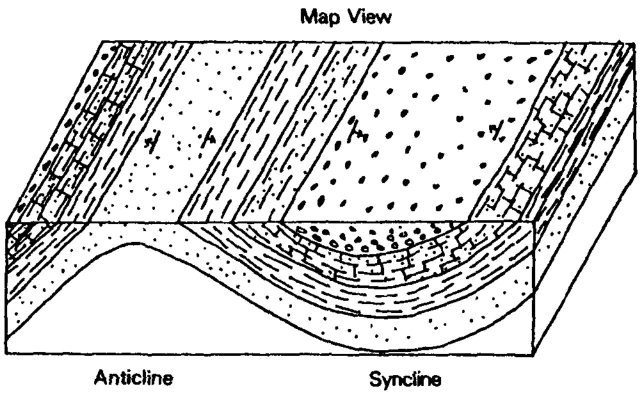
Glaciers advanced and retreated many times, reworking, overriding, and incorporating sediments from previous advances into the ice, subsequently redepositing them elsewhere. There was a constant inversion of topography as buried ice melted causing adjacent, waterlogged till to slump into the low areas. During advances, the ice might have overridden older outwash layers so that upon melting these sand and gravel deposits were covered by a younger layer of till. Regardless of the cause, the final effect is one of complexity of origin, history, and stratigraphy. When working with glacial till deposits, it is nearly always impossible to predict the lateral extent or thickness of a particular lithology in the subsurface. Surficial stratified drift is more uniform than till in thickness, extent, and texture.

Geologic Structure

A general law of geology is that in any sequence of sedimentary rocks that has not been disturbed by folding or faulting, the youngest unit is on the top. A second general law is that sedimentary rocks are deposited in a horizontal or nearly horizontal position. The fact that rocks are found overturned, displaced vertically or laterally, and squeezed into open or tight folds, clearly indicates that the crust of the earth is a dynamic system. There is a constant battle between the forces of destruction (erosion) and construction (earth movements).

Folding

Rocks, folded by compressional forces, are common in and adjacent to former or existing mountain ranges. The folds range from a few inches to 50 miles or so across. Anticlines are rocks folded upward into an arch. Their counterpart, synclines, are folded downward like a valley (fig. 1-1). A monocline is a flecture in which the rocks are horizontal, or nearly so, on either side of the flecture.



The arrow indicates the direction of dip. In an anticline, the rocks dip away from the crest and in a syncline they dip toward the center.

Figure 1-1. Dip and Strike Symbols Commonly Shown on Geologic Maps

Although many rocks have been folded into various structures, this does not mean that these same structures form similar topographic features. As the folding takes place over eons, the forces of erosion attempt to maintain a low profile. As uplift continues, erosion removes weathering products from the rising mass, carrying them to other places of deposition. The final topography is related to the erodibility of the rocks, with resistant strata, such as sandstone, forming ridges, and the less resistant material, such as shale, forming valleys (fig. 1-2). Consequently, the geologic structure of an area may bear little resemblance to its topography.

The structure of an area can be determined from field studies or a geologic map, if one exists. Various types of folds and their dimensions appear as unusual patterns on geologic maps. An anticline, for example, will be depicted as a series of rock units in which the oldest is in the middle, while a syncline is represented by the youngest rock in the center. More or less equidimensional anticlines and synclines are termed domes and basins, respectively.

The inclination of the top of a fold is the plunge. Folds may be *symmetrical, asymmetrical, overturned*, or recumbent. The inclination of the rocks is indicated by dip and strike symbols. The strike is perpendicular to the dip and the degree of dip is commonly shown by a number. The dip may range from less than a degree to vertical.

Unconformities

An unconformity is a break in the geologic record. It is caused by a cessation in deposition that is followed by erosion and subsequent deposition. The geologic record is lost by the period of erosion because the rocks that contained the record were removed.

If a sequence of strata is horizontal but the contact between two rock groups in the sequence represents an erosional surface, that surface is said to be a disconformity (fig. 1-3). Where a sequence of strata has been tilted and eroded and then younger, horizontal rocks are deposited over them, the contact is an angular unconformity. A nonconformity occurs where eroded

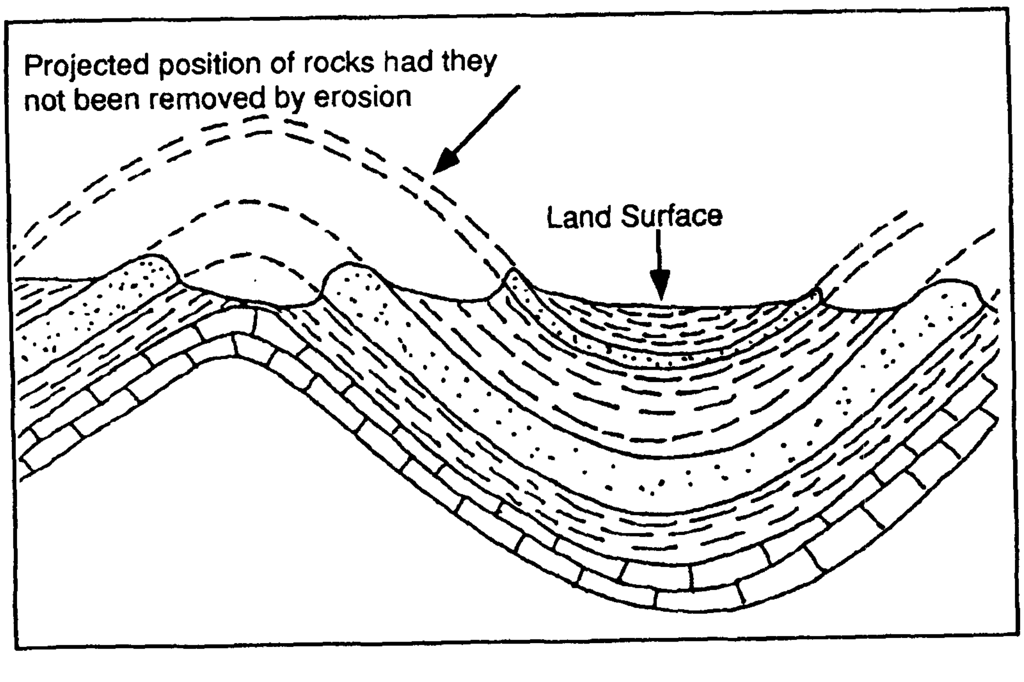


Figure 1-2. Geologic Structure May Influence Surface Topography

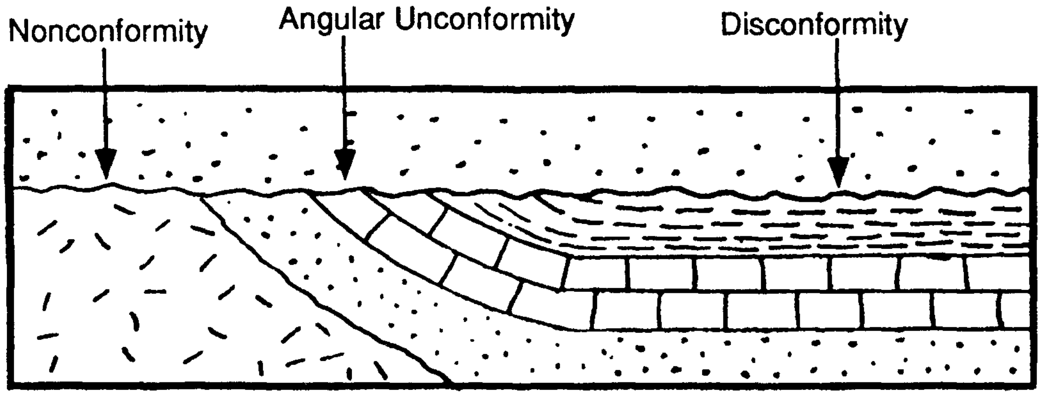


Figure 1-3. An Unconformity Represents a Break in the Geologic Record

igneous or metamorphic rocks are overlain by sedimentary rocks.

Fractures

Fractures in rocks are either joints or faults. A joint is a fracture along which no movement has taken place; a fault implies movement. Movement along faults is as little as a few inches to tens of miles. Probably all consolidated rocks and a good share of the unconsolidated deposits contain joints. Joints may exert a major control on water movement and chemical quality. Characteristically joints are open and serve as major conduits or pipes. Water can move through them quickly, perhaps carrying contaminants, and, being open, the filtration effect is lost. It is a good possibility that the outbreak of many waterborne diseases that can be tied to ground-water supplies is the result of the transmission of infectious agents through fractures to wells and springs.

Faults are most common in the deformed rocks of mountain ranges, suggesting either lengthening or shortening of the crust. Movement along a fault may be horizontal, vertical, or a combination. The most common types of faults are called normal, reverse, and lateral (fig. 1-4). A normal fault, which indicates stretching of the crust, is one in which the upper or hanging wall has moved down relative to the lower or foot wall. The Red Sea, Dead Sea, and the large lake basins in the east African highlands, among many others, lie in grabens, which are blocks bounded by normal faults (fig. 1-4). A reverse or thrust fault implies compression and shortening of the crust. It is distinguished by the fact that the hanging wall has moved up relative to the foot wall. A lateral fault is one in which the movement has been largely horizontal. The San Andreas Fault, extending some 600 miles from San Francisco Bay to the Gulf of California, is the most notable lateral fault in the United States. It was movement along this fault the produced the 1906 San Francisco earthquake.

Geologic Time

Geologic time deals with the relation between the emplacement or disturbance of rocks and time. In order to provide some standard classification, the geologic time scale was developed (table 1-2). It is based on a sequence of rocks that were deposited during a particular time interval. Commonly the divisions are based on some type of unconformity. In considering geologic time, three types of units are defined. These are rock units, time-rock units, and time units.

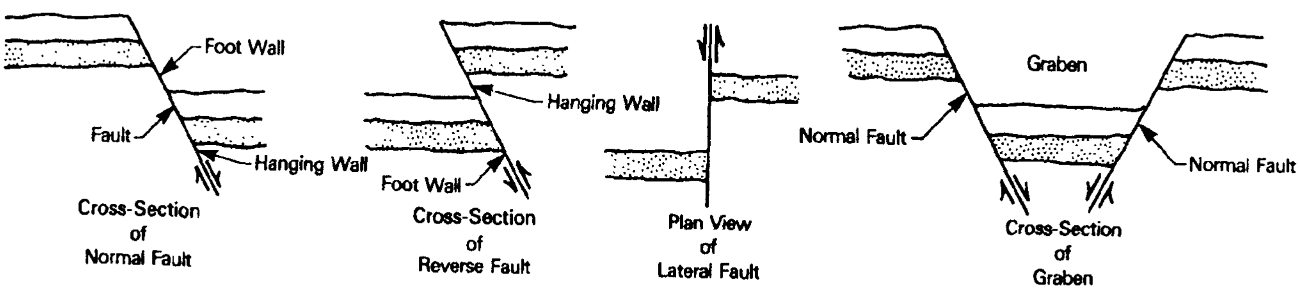


Figure 1-4. Cross Sections of Normal, Reverse and Lateral Faults

Era	Period	Epoch	Millions of Years Ago
Cenozoic	Quaternary	Recent	
		Pleistocene	0-2
	Tertiary	Pliocene	2-13
		Miocene	13-25
		Oligocene	25-36
		Eocene	36-58
		Paleocene	58-63
Mesozoic	Cretaceous		63-135
	Jurassic		135-181
	Triassic		181-230
Paleozoic	Permian		230-280
	Pennsylvanian		280-310
	Mississippian		310-345
	Devonian		345-405
	Silurian		405-425
	Ordovician		425-500
	Cambrian		500-600
Precambrian	Lasted at least 2.5 billion years		

Table 1-2. Geologic Time Scale

Rock Units

A rock unit refers to some particular lithology. These may be further divided into geologic formations, which are of sufficient size and uniformity to be mapped in the field. The Pierre Shale, for example, is a widespread and, in places, thick geologic formation that extends over much of the Northern Great Plains. Formations can also be divided into smaller units called members. Formations have a geographic name that may be coupled with a term that describes the major rock type. Two or more formations comprise a group.

Time and Time-Rock Units

Time-rock units refer to the rock that was deposited during a certain period of time. These units are divided into system, series, and stage. Time units refer to the time during which a sequence of rocks were deposited. The time-rock term, system, has the equivalent time term, period. That is, during the Cretaceous Period rocks of the Cretaceous System were deposited and they consist of many groups and formations. Time units are named in such a way that the eras reflect the complexity of life forms that existed, such as the Mesozoic or "middle life." System or period nomenclature largely is based on the geographic location in which the rocks were first described, such as Jurassic, which relates to the Jura Mountains of Europe.

The terms used by geologists to describe rocks relative to geologic time are useful to the ground-water investigator in that they allow one to better perceive a regional geologic situation. The terms alone have no significance as far as water-bearing properties are concerned.

Geologic Maps And Cross Sections

Geologists use a number of techniques to graphically represent surface and subsurface conditions. These include surficial geologic maps, columnar sections, cross-sections of the subsurface, maps that show the configuration of the surface of a geologic unit, such as the bedrock beneath glacial deposits, maps that indicate the thickness or grain size of a particular unit, a variety of contour maps, and a whole host of others.

A surficial geologic map depicts the geographic extent of formations and their structure. Columnar sections describe the vertical distribution of rock units, their lithology, and thickness. Geologic cross sections attempt to illustrate the subsurface distribution of rock units between points of control, such as outcrops or well bores. An isopach map shows the geographic range in thickness of a unit. These maps and cross-sections are based largely or entirely on well logs, which are descriptions of earth material penetrated during the drilling of a well or test hole.

Whatever the type of graphical representation, it must be remembered that maps of the subsurface and cross-sections represent only interpretations, most of which are based on scanty data. In reality, they are merely graphical renditions that are presumably based on scientific thought, a knowledge of depositional characteristics of rock units, and a data base that provides some control. They are not exact because the features they attempt to show are complex, nearly always hidden from view, and difficult to sample.

All things considered, graphical representations are exceedingly useful, if not essential, to subsurface studies. On the other hand, a particular drawing that is prepared for one purpose may not be suitable for another purpose even though the same units are involved. This is largely due to scale and generalizations.

A geologic map of a glaciated area is shown in fig. 1-5. The upland area is mantled by glacial till (Qgm) and the surficial material covering the relatively flat flood plain has been mapped as alluvium (Qal). Beneath the alluvial cover are other deposits of glacial origin that consist of glacial till, outwash, and glacial lake deposits. A water well drillers log of a boring in the valley states "this well is just like all of the others in the valley" and that the upper 70 feet of the valley fill consists of a "mixture of clay, sand, silt, and boulders." This is underlain by 30 feet of "water sand," which is the aquifer. The aquifer overlies "slate, jingle rock, and coal." The terminology may be quaint, but it is nonetheless a vocabulary that must be interpreted.

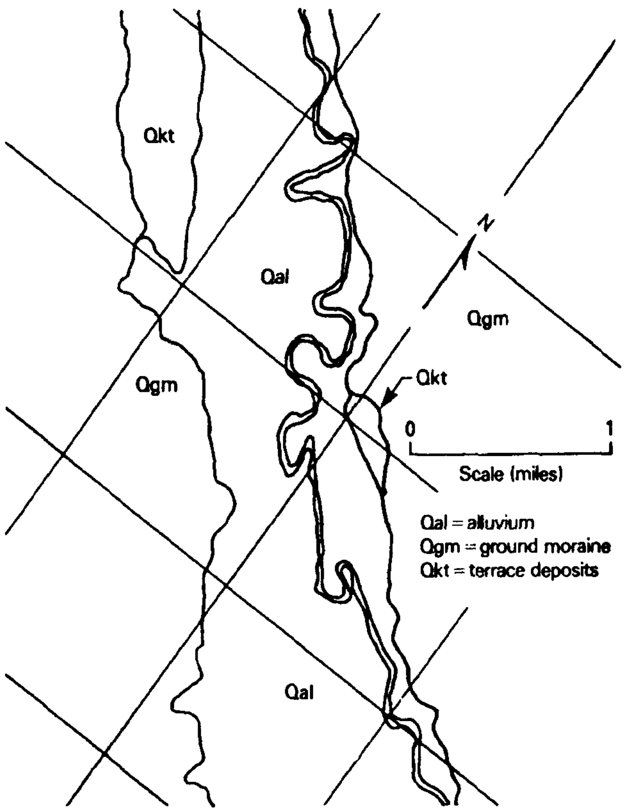


Figure 1-5. Generalized Geologic Map of a Glaciated Area Along the Souris River Valley in Central North Dakota

Examination of the local geology, as evidenced by strata that crop out along the hill sides, indicates that the bedrock or older material that underlies the glacial drift consists of shale, sandstone cemented by calcite, and lignite, which is an immature coal. These are the geologic terms, at least in this area, for "slate, jingle rock, and coal," respectively.

For generalized purposes, it is possible to use the drillers log to construct a cross section across or along the stream valley (fig. 1-6). In this case, one would assume for the sake of simplicity, the existence of an

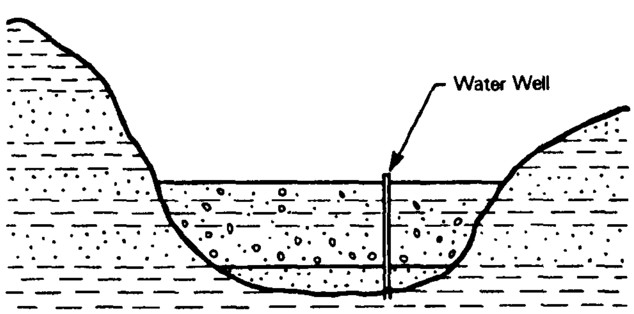


Figure 1-6. Generalized Geologic Cross Section of the Souris River Valley Based on Driller's Log

aquifer that is rather uniform in composition and thickness. A second generation cross section, shown in fig. 1-7, is based on several bore-hole logs described by a geologist who collected samples as the holes were being drilled. Notice in this figure that the subsurface appears to be much more complex, consisting of several isolated permeable units that are incorporated within the fine-grained glacial deposits that fill the valley. In addition, the aquifer does not consist of a uniform thickness of sand, but rather a unit that ranges from 30 to 105 feet in thickness and from sand to a mixture of sand and gravel. The water-bearing characteristics of each of these units are all different. This cross section too is quite generalized, which becomes evident as one examines an actual log of one of the bore holes (table 1-3).

In addition to showing more accurately the composition of the subsurface, well logs also can provide some interesting clues concerning the relative permeabilities of the water-bearing units. Referring to Table 1-4, a generalized log of well 1 describing the depth interval ranging from 62 to 92 feet, contains the remark "losing water" and in well 5, at a depths of 80 to 120 feet, is the notation, "3 bags of bentonite." In the first case "losing water" means that the material being penetrated by the drill bit from 62 to 92 feet was more permeable than the annulus of the cutting-filled bore hole. Some of the water used for drilling, which is pumped down the hole through the drill pipe to remove the cuttings, found it easier to move out into the formation than to flow back up the hole. The remark is a good indication of a permeability that is higher than that present in those sections where water was not being lost.

In the case of well 5, the material extending from 80 to 120 feet was so permeable that much of the drilling fluid was moving into the formation and there was no return of the cuttings. To regain circulation, bentonite, or to use the field term, "mud," was added to the drilling fluid to seal the permeable zone. Even though the geologist described the aquifer materials from both zones similarly, the section in well 5 is more permeable than the one in well 1, which in turn is more permeable than the other coarse-grained units penetrated where there was no fluid loss.

The three most important points to be remembered here are, first, graphical representations of the surface or subsurface geology are merely guesses of what might actually exist, and even these depend to some extent on the original intended usage. Secondly, the subsurface is far more complex than is usually anticipated, particularly in regard to unconsolidated deposits. Finally, evaluating the original data, such as well logs, might lead to a better appraisal of the

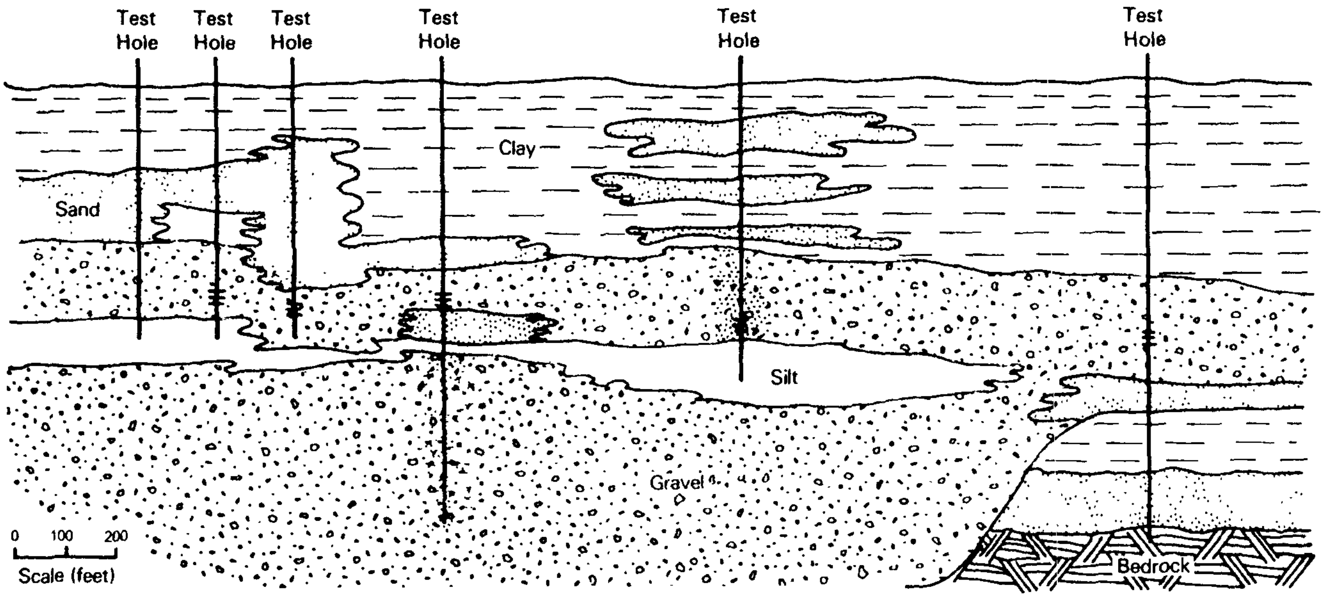


Figure 1-7. Geologic Cross Section of the Souris River Valley Based on Detailed Logs of Test Holes

Sample Description and Drilling Condition	Depth (ft)
Topsoil, silty clay, black	0-1
Clay, silty, yellow brown, poorly consolidated	1-5
Clay, silty, yellow gray, soft, moderately compacted	5-10
Clay, silty, as above, silty layers, soft	10-15
Silty, clayey, gray, soft, uniform drilling	15-20
Clay, silty, some fine to medium sand, gray	20-30
Clay, gray to black, soft, very tight	30-40
Clay, as above, gravelly near top	40-50
Clay, as above, no gravel	50-60
Clay, as above, very silty in spots, gray	60-70
Clay and silt, very easy drilling	70-80
Clay, as above to gravel, fine to coarse, sandy, thin clay layers, taking lots of water	80-90
Gravel, as above, some clay near top, very rough drilling, mixed three bags of mud, lots of lignite chips	90-100
Gravel, as above, cobbles and boulders	100-120
Gravel, as above, to sand, fine to coarse, lots of lignite, much easier drilling	120-130
Clay, gravelly and rocky, rough drilling, poor sample return	130-140
Sandy clay, gravelly and rocky, rough drilling, poor sample return (till)	140-150
Sandy clay, as above, poor sample return	150-160
Clay, sandy, gray, soft, plastic, noncalcareous	160-170
Clay, sandy, as above, tight, uniform drilling	170-180
Clay, as above, much less sand, gray, soft, tight, plastic	180-190
Clay, as above, no sand, good sample return	190-200
Clay, as above	200-210

Table 1-3. Geologist's Log of a Test Hole, Souris River Valley, North Dakota

subsurface, an appraisal that far surpasses the use of generalized lithologic logs alone.

Ground Water In Igneous And Metamorphic Rocks

Nearly all of the porosity and permeability of igneous and metamorphic rocks are the result of secondary openings, such as fractures, faults, and the dissolution of certain minerals. A few notable exceptions include large lava tunnels present in some flows, interflow or coarse sedimentary layers between individual lava flows, and deposits of selected pyroclastic materials.

Because the openings in igneous and metamorphic rocks are, volumetrically speaking, quite small, rocks of this type are poor suppliers of ground water. Moreover, the supplies that are available commonly drain rapidly after a period of recharge by infiltration of precipitation. In addition they are subject to contamination from the surface where these rocks crop out.

The width, spacing, and depth of fractures ranges widely, as do their origin. Fracture widths vary from about .0008 inches the surface to .003 inches at a depth of 200 feet, while spacing increased from 5 to 10 feet near the surface to 15 to 35 feet at depth in the Front Range of the Rocky Mountains (Snow, 1968). In the same area porosity decreased from below 300 feet or so, but there are many recorded exceptions. Exfoliation fractures in the crystalline rocks of the Piedmont near Atlanta, GA range from 1 to 8 inches in width (Cressler and others, 1983).

Material	Depth (ft)
Test Hole 1	
Fill	0-3
Silt, olive-gray	3-14
Sand, fine-medium	14-21
Silt, sandy, gray	21-25
Clay, gray	25-29
Sand, fine-coarse	29-47
Clay, gray	47-62
Gravel, fine to coarse, losing water	62-92
Silt, sandy, gray	92-100
Observation well depth 80 feet	
Test Hole 2	
Fill	0-2
Clay, silty and sandy, gray	2-17
Clay, very sandy, gray	17-19
Sand, fine-medium	19-60
Sand, fine-coarse with gravel	60-80
Gravel, coarse, 2 bags bentonite and bran	80-100
Observation well depth 88 feet	
Test Hole 3	
Silt, yellow	0-5
Clay, silty, black	5-15
Sand, fine to coarse	15-29
Clay, silty, gray	29-65
Sand, medium-coarse, some gravel	65-69
Gravel, sandy, taking water	69-88
Sand, fine to medium, abundant chips of lignite	88-170
Observation well depth 84 feet	
Test Hole 4	
Fill	0-5
Silt, brown	5-12
Sand, fine-medium	12-28
Clay, silty and sandy, gray	28-37
Sand, fine	37-49
Clay, dark gray	49-55
Sand, fine	55-61
Clay, sandy, gray	61-66
Sand, fine-coarse, some gravel	66-103
Silt, gray	103-120
Observation well depth 96 feet	
Test Hole 5	
Clay, silty, brown	0-10
Silt, clayey, gray	10-80
Gravel, fine-coarse, sandy, taking lots of water 3 bags bentonite	80-120
Sand, fine to coarse, gravelly	120-130
Clay, gravelly and rocky (till)	130-150
Sand, fine, Fort Union Group	150-180
Observation well depth 100 feet	

Table 1-4. Generalized Geologic Logs of Five Test Holes, Souris River Valley, North Dakota

The difficulty of evaluating water and contaminant movement in fractured rocks is that the actual direction of movement may not be in the direction of decreasing head, but rather in some different though related direction. The problem is further compounded by the difficulty in locating the fractures. Because of these characteristics, evaluation of water availability, direction of movement, and velocity is exceedingly difficult. As a general rule in the eastern part of the United States, well yields, and therefore fractures, permeability, and porosity, are greater in valleys and broad ravines than on flat uplands, which in turn is higher than on hill slopes and hill crests.

Unless some special circumstance exists, water obtained from igneous and metamorphic rocks is nearly always of excellent chemical quality. Dissolved solids are commonly less than 100 mg/L. Water from metamorphosed carbonate rocks may have moderate to high concentrations of hardness.

Ground Water In Sedimentary Rocks

Usable supplies of ground water can be obtained from all types of sedimentary rocks, but the fine-grained strata, such as shale and siltstone, may only provide a few gallons per day and even this can be highly mineralized. Even though fine-grained rocks may have relatively high porosities, the primary permeability is very low. On the other hand, shale is likely to contain a great number of joints that are both closely spaced and extend to depths of several tens of feet. Therefore, rather than being impermeable, they can be quite transmissive. This is of considerable importance in waste disposal schemes because insufficient attention might be paid during engineering design to the potential for flow through fractures. In addition, the leachate that is formed as water infiltrates through waste might be small in quantity but highly mineralized. Because of the low bulk permeability, it would be difficult to remove the contaminated water or even to properly locate monitoring wells.

From another perspective, fine-grained sedimentary rocks, owing to their high porosity, can store huge quantities of water. Some of this water can be released to adjacent aquifers when a head difference is developed by pumping. No doubt fine-grained confining units provide, on a regional scale, a great deal of water to aquifer systems. The porosity, however, decreases with depth because of compaction brought about by the weight of overlying sediments.

The porosity of sandstones range from less than 1 percent to a maximum of about 30 percent. This is a function of sorting, grain shape, and cementation. Cementation can be variable both in space and time and on outcrops can differ greatly from that in the subsurface.

Fractures also play an important role in the movement of fluids through sandstones and transmissivities may be as much as two orders of magnitude greater in a fractured rock than in an unfractured part of the same geologic formation.

Sandstone units that were deposited in a marine or near marine environment can be very wide spread, covering tens of thousands of square miles, such as the St. Peter Sandstone of Cambrian age. Those representing ancient alluvial channel fills, deltas, and related environments of deposition are more likely to be discontinuous and erratic in thickness. Individual units are exceedingly difficult to trace in the subsurface. Regional ground-water flow and storage may be strongly influenced by the geologic structure.

Carbonate rocks are formed in many different environments and the original porosity and permeability are modified rapidly after burial. Some special carbonate rocks, such as coquina and some breccias, may remain very porous and permeable, but these are the exception.

It is the presence of fractures and other secondary openings that develop high yielding carbonate aquifers. One important aspect is the change from calcite to dolomite ($CaMg[CO_3]_2$), which results in a volumetric reduction of 13 percent and the creation of considerable pore space. Of particular importance and also concern in many of the carbonate regions of the world, is the dissolution of carbonates along fractures and bedding planes by circulating ground water. This is the manner in which caves and sinkholes are formed. As dissolution progresses upward in a cave, the overlying rocks may collapse to form a sinkhole that contains water if the cavity extends below the water table. Regions in which there has been extensive dissolution of carbonates leading to the formation of caves, underground rivers, and sinkholes, are called karst. Notable examples include parts of Missouri, Indiana, and Kentucky.

Karst areas are particularly troublesome, even though they can provide large quantities of water to wells and springs. They are easily contaminated, and it is commonly difficult to trace the contaminant because the water can flow very rapidly, and there is no filtering action to degrade the waste. Not uncommonly a well owner may be unaware that he is consuming unsafe water. An individual in Kentucky became concerned because his well yield had declined. The well, which drew water from a relatively shallow cave below the water table, was cased with a pipe, on the end of which was a screen. When the screen was pulled, it was found to be completely coated with fibrous material. The owner was disconcerted to learn that the fibrous covering was derived from toilet paper.

Ground Water In Unconsolidated Sediments

Unconsolidated sediments accumulate in many different environments, all of which leave their trademark on the characteristics of the deposit. Some are thick and areally extensive, as the alluvial fill in the Basin and Range Province, others are exceedingly long and narrow, such as the alluvial deposits along streams and rivers, and others may cover only a few hundred square feet, like some glacial forms. In addition to serving as major aquifers, unconsolidated sediments are also important as sources of raw materials for construction.

Although closely related to sorting, the porosities of unconsolidated materials range from less than 1 to more than 90 percent, the latter representing uncompacted mud. Permeabilities also range widely. Cementing of some type and degree is probably universal, but not obvious, with silt and clay being the predominant form.

Most unconsolidated sediments owe their emplacement to running water and, consequently, some sorting is expected. On the other hand, water as an agent of transportation will vary in both volume and velocity, which is climate dependent, and this will leave an imprint on the sediments. It is to be expected that stream related material, which most unconsolidated material is, will be variable in extent, thickness, and grain size. Other than this, one can draw no general guidelines; therefore, it is essential to develop some knowledge of the resulting stratigraphy that is characteristic of the most common environments of deposition. The water-bearing properties of glacial drift, of course, are exceedingly variable, but stratified drift is more uniform and better sorted than glacial till.

Relation Between Geology, Climate, and Ground-Water Quality

The availability of ground-water supplies and their chemical quality are closely related to precipitation. As a general rule, the least mineralized water, both in streams and underground, occurs in areas of the greatest amount of rainfall. Inland, precipitation decreases, water supplies diminish, and the quality deteriorates. The mineral composition of water-bearing rocks exerts a strong influence on ground-water quality and thus, the solubility of the rocks may override the role of precipitation.

Where precipitation exceeds 40 inches per year, shallow ground water usually contains less than 500 mg/L and commonly less than 250 mg/L of dissolved solids. Where precipitation ranges between 20 and 40 inches, dissolved solids may range between 400 and 1,000 mg/L, and in drier regions they commonly exceed 1,000 mg/L.

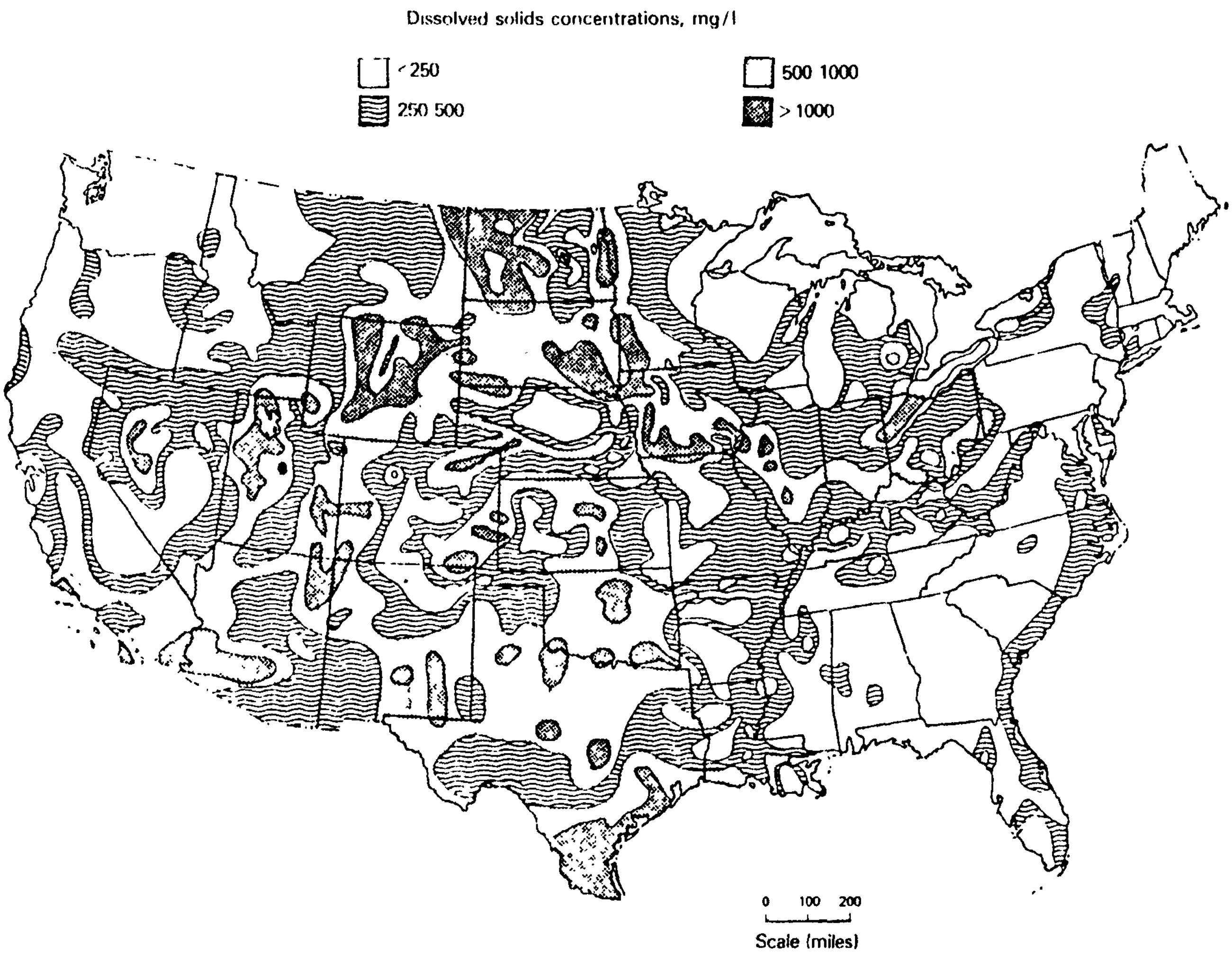


Figure 1-8. Dissolved Solids Concentrations in Ground Water Used for Drinking in the United States (from Pettyjohn and others, 1979)

The dissolved solids concentration of ground water increases toward the interior of the continent. The increase is closely related to precipitation and the solubility of the aquifer framework. The least mineralized ground water is found in a broad belt that extends southward from the New England states, along the Atlantic Coast to Florida, and then continues to parallel much of the Gulf Coast. Similarly, along the Pacific Coast from Washington to central California, the mineral content is also very low. Throughout this belt, dissolved solids concentrations generally are less than 250 mg/L and commonly less than 100 mg/L (fig. 1-8).

The Appalachian region consists of a sequence of strata that range from nearly flat-lying to complexly folded and faulted. Likewise, ground-water quality in this region also is highly variable, being generally harder and containing more dissolved minerals than does water along the coastal belt. Much of the difference in quality, however, is related to the abundance of carbonate aquifers, which provide waters rich in calcium and magnesium.

Westward from the Appalachian Mountains to about the position of the 20-inch precipitation line (eastern North Dakota to Texas), dissolved solids in ground water progressively increase. They are generally less than 1,000 mg/L and are most commonly in the 250 to 750 mg/L range. The water is moderately to very hard, and in some areas concentrations of sulfate and chloride are excessive.

From the 20-inch precipitation line westward to the northern Rocky Mountains, dissolved solids are in the 500 to 1,500 mg/L range. Much of the water from glacial drift and bedrock formations is very hard and contains significant concentrations of calcium sulfate. Other bedrock formations may contain soft sodium bicarbonate, sodium sulfate, or sodium chloride water.

Throughout much of the Rocky Mountains, ground-water quality is variable, although the dissolved solids concentrations commonly range between 250 and 750 mg/L. Stretching southward from Washington to southern California, Arizona, and New Mexico is a vast desert region. Here the difference in quality is wide and dissolved solids generally exceed 750 mg/L. In the central parts of some desert basins the ground water is highly mineralized, but along the mountain flanks the mineral content may be quite low.

Extremely hard water is found over much of the Interior Lowlands, Great Plains, Colorado Plateau, and Great Basin. Isolated areas of high hardness are present in northwestern New York, eastern North Carolina, the southern tip of Florida, northern Ohio, and parts of southern California. In general, the hardness is of the carbonate type.

On a regional level, chloride does not appear to be a significant problem, although it is troublesome locally due largely to industrial activities, the intrusion of seawater caused by overpumping coastal aquifers, or interaquifer leakage related to pressure declines brought about by withdrawals.

In many locations, sulfate levels exceed the federal recommended limit of 250 mg/L; regionally sulfate may be a problem only in the Great Plains, eastern Colorado Plateau, Ohio, and Indiana. Iron problems are ubiquitous because concentrations exceeding only .3 mg/L will cause staining of clothing and fixtures. Fluoride is abnormally high in several areas, particularly parts of western Texas, Iowa, Illinois, Indiana, Ohio, New Mexico, Wyoming, Utah, Nevada, Kansas, New Hampshire, Arizona, Colorado, North and South Dakota, and Louisiana.

A water-quality problem of growing concern, particularly in irrigated regions, is nitrate, which is derived from fertilizers, sewage, and through natural causes. When consumed by infants less than six months old for a period of time, high nitrate concentrations can cause a disease known as "blue babies." This occurs because the child's blood cannot carry sufficient oxygen; the disease is easily overcome by using low nitrate water for formula preparation. Despite the fact that nitrate concentrations in ground water appear to have been increasing in many areas during the last 30 years or so, there have been no reported incidences of "blue babies" for more than 20 years, at least in the states that comprise the Great Plains.

Conclusions

In detail, the study of geology is complex, but the principles outlined above should be sufficient for a general understanding of the topic, particularly as it relates to ground water. If interested in a more definitive treatment, the reader should examine the references at the end of the chapter.

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Chapter 2

CLASSIFICATION OF GROUND-WATER REGIONS

To describe concisely ground-water conditions in the United States, it is necessary to divide the country into regions in which these conditions are generally similar. Because the presence and availability of ground water depends primarily on geologic conditions, ground-water regions also are areas in which the composition, arrangement, and structure of rock units are similar (Heath, 1982).

To divide the country into ground-water regions, it is necessary to develop a classification that identifies features of ground-water systems that affect the occurrence and availability of ground water. The five features pertinent to such a classification are: (l) the components of the system and their arrangement, (2) the nature of the water-bearing openings of the dominant aquifer or aquifers with respect to whether they are of primary or secondary origin, (3) the mineral composition of the rock matrix of the dominant aquifers with respect to whether it is soluble or insoluble, (4) the water storage and transmission characteristics of the dominant aquifer or aquifers, and (5) the nature and location of recharge and discharge areas.

The first two of these features are primary criteria used in all delineations of ground-water regions. The remaining three are secondary criteria that are useful in subdividing what might otherwise be large and unwieldy regions into areas that are more homogeneous and, therefore, more convenient for descriptive purposes. Table 2-1 lists each of the five features together with explanatory information. The fact that most of the features are more or less interrelated is readily apparent from the comments in the column headed "Significance of Feature."

Ground-Water Regions of the United States

On the basis of the criteria listed above the United States, exclusive of Alaska and Hawaii, can be divided into 11 ground-water regions.

Figure 2-1 shows the boundaries of these 11 regions. A special area, region 12, which consists of those segments of the valleys of perennial streams that are underlain by sand and gravel thick enough to be hydrologically significant (thicknesses generally more than about 26 feet), is shown in Figure 2-2.

The nature and extent of the dominant aquifers and their relations to other units of the ground-water system are the primary criteria used in delineating the regions. Consequently, the boundaries of the regions generally coincide with major geologic boundaries and at most places do not coincide with drainage divides. Although this lack of coincidence emphasizes that the physical characteristics of ground-water systems and stream systems are controlled by different factors, it does not mean that the two systems are not related. Ground-water systems and stream systems are intimately related, as shown in the following discussions of each of the ground-water regions.

1. Western Mountain Ranges

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

The Western Mountain Ranges, shown in Figure 2-3, encompass three areas totaling 278,000 mi^2. 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 of South Dakota in which Precambrian rocks are exposed.

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

Feature	Aspect	Range in Conditions	Significance of Feature
Component of the system	Unconfined aquifer	Thin, discontinuous, hydrologically insignificant. Minior aquifer, serves primarily as a storage reservoir and recharge conduit for underlying aquifer. The dominant aquifer.	Affect response of the system to pumpage and other stresses. Affect recharge and discharge conditions. Determine susceptibility to pollution.
	Confining beds	Not present, or hydrologically insignificant. Thin, markedly discontinuous, or very leaky. Thick, extensive, and impermeable. Complexly interbedded with aquifers or productive zones.	
	Confined aquifers	Not present, or hydrologically insignificant. Thin or not highly productive. Multiple thin aquifers interbedded with nonproductive zones. The dominant aquifer—thick and productive.	
	Presence and arrangements of components	A single, unconfined aquifer. Two interconnected aquifers of essentially equal hydrologic importance. A three-unit system consisting of an unconfined aquifer, a confining bed, and confined aquifer. A complexly interbedded sequence of aquifers and confining beds.	
Water-bearing openings of dominant aquifer	Primary openings	Pores in unconsolidated deposits. Pores in semiconsolidated rocks. Pores, tubes, and cooling fractures in volcanic (extrusive-igneous) rocks.	Control water-storage and transmission characteristics. Affect disperson and dilution of wastes.
	Secondary openings	Fractures and faults in crystalline and consolidated sedimentary rocks. Solution-enlarged openings in limestones and other soluble rocks.	
Composition of rock matrix of dominant aquifer	Insoluble	Essentially insoluble. Both relatively insoluble and soluble constituents.	Affects water-storage and transmission characteristics. Has major influence on water quality.
	Soluble	Relatively soluble.	
Storage and transmission characteristics of dominant aquifer	Porosity	Large, as in well-sorted, unconsolidated deposits. Moderate, as in poorly-sorted unconsolidated deposits and semiconsolidated rocks. Small, as in fractured crystalline and consolidated sedimentary rocks.	Control response to pumpage and other stresses. Determine yield of wells. Affect long-term yield of system. Affect rate at which pollutants move.
	Transmissivity	Large, as in cavernous limestones, some lava flows, and clean gravels. Moderate, as in well-sorted, coarse-grained sands, and semiconsolidated limestones. Small, as in poorly-sorted, fine-grained deposits and most fractured rocks. Very small, as in confining beds.	
Recharge and discharge conditions of dominant aquifer	Recharge	In upland areas between streams, particularly in humid regions. Through channels of losing streams. Largely or entirely by leakage across confining beds from adjacent aquifers.	Affect response to stress and long-term yields. Determine susceptibility to pollution. Affect water quality.
	Discharge	Through springs or by seepage to stream channels, estuaries, or the ocean. By evaporation on flood plains and in basin "sinks." By seepage across confining beds into adjacent aquifers.	

Table 2-1. Features of Ground-Water Systems Useful in the Delineation of Ground-Water Regions

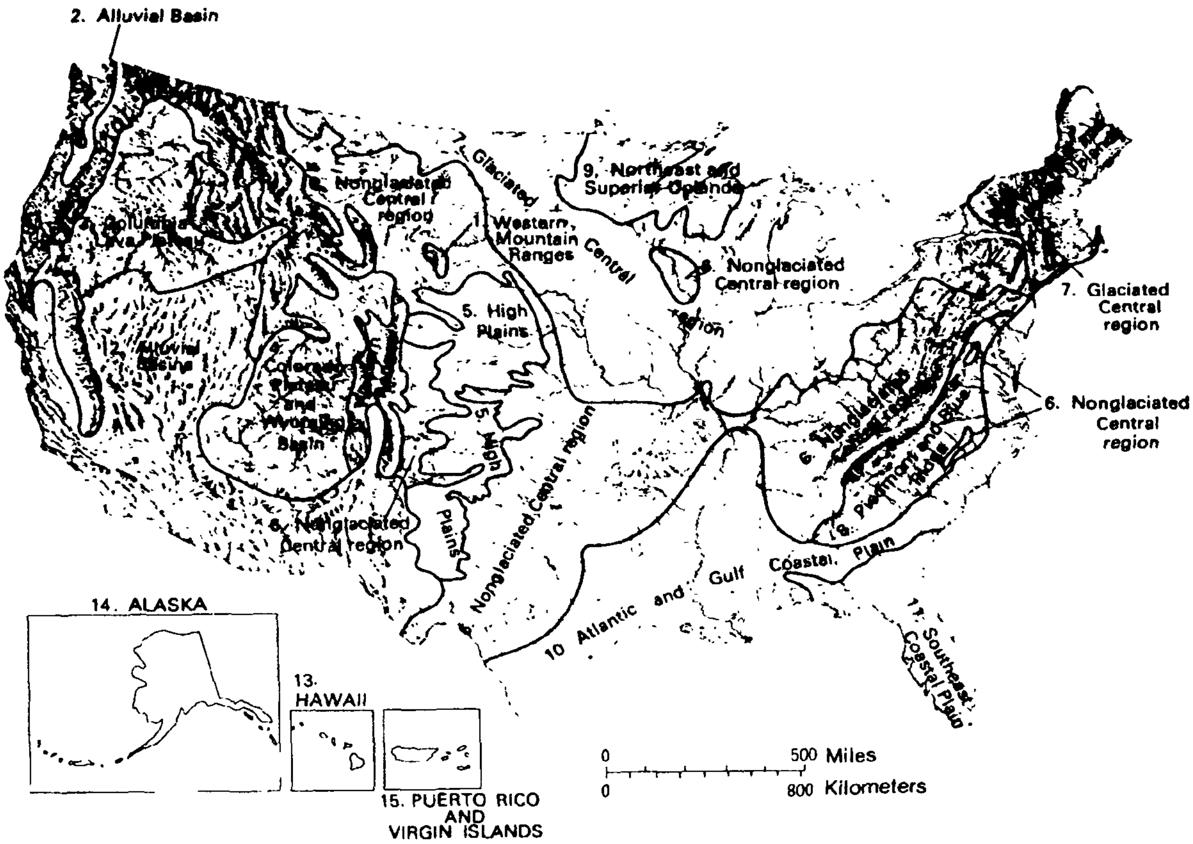

Figure 2-1. Ground-Water Regions Used in This Report [The Alluvial Valleys Region (region 12) is shown on figure 2-2]

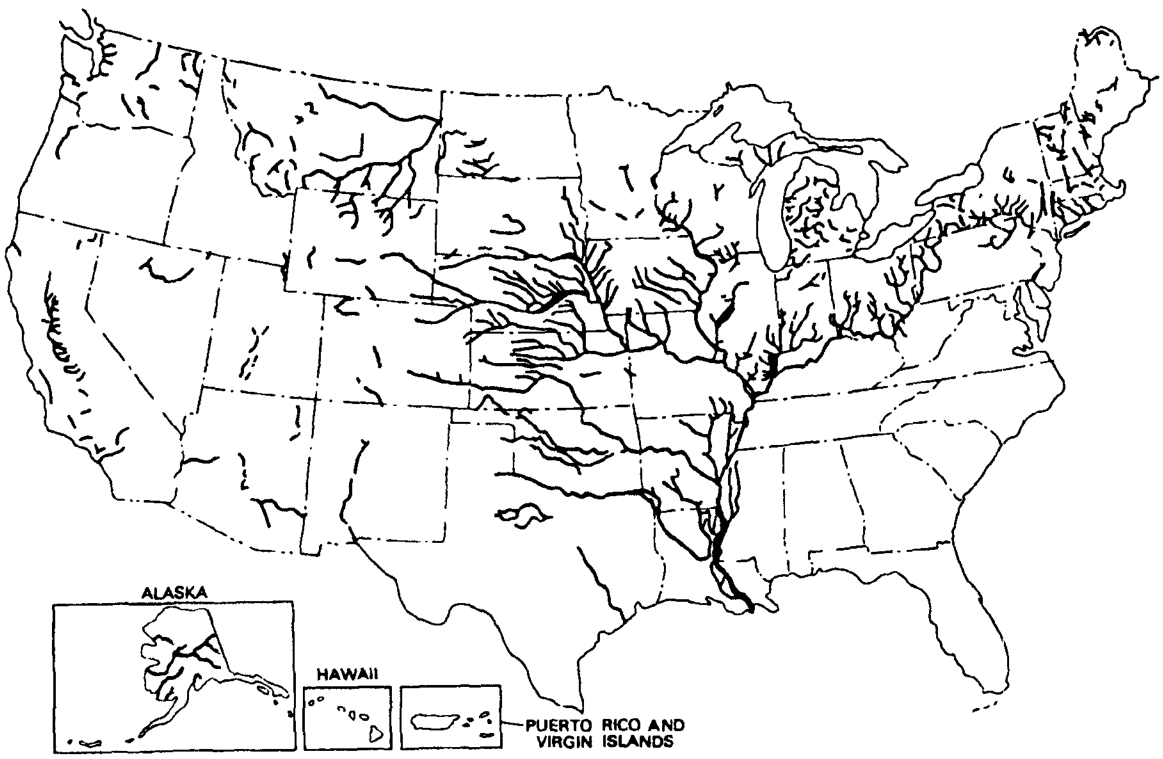

Figure 2-2. Alluvial Valleys Ground-Water Region

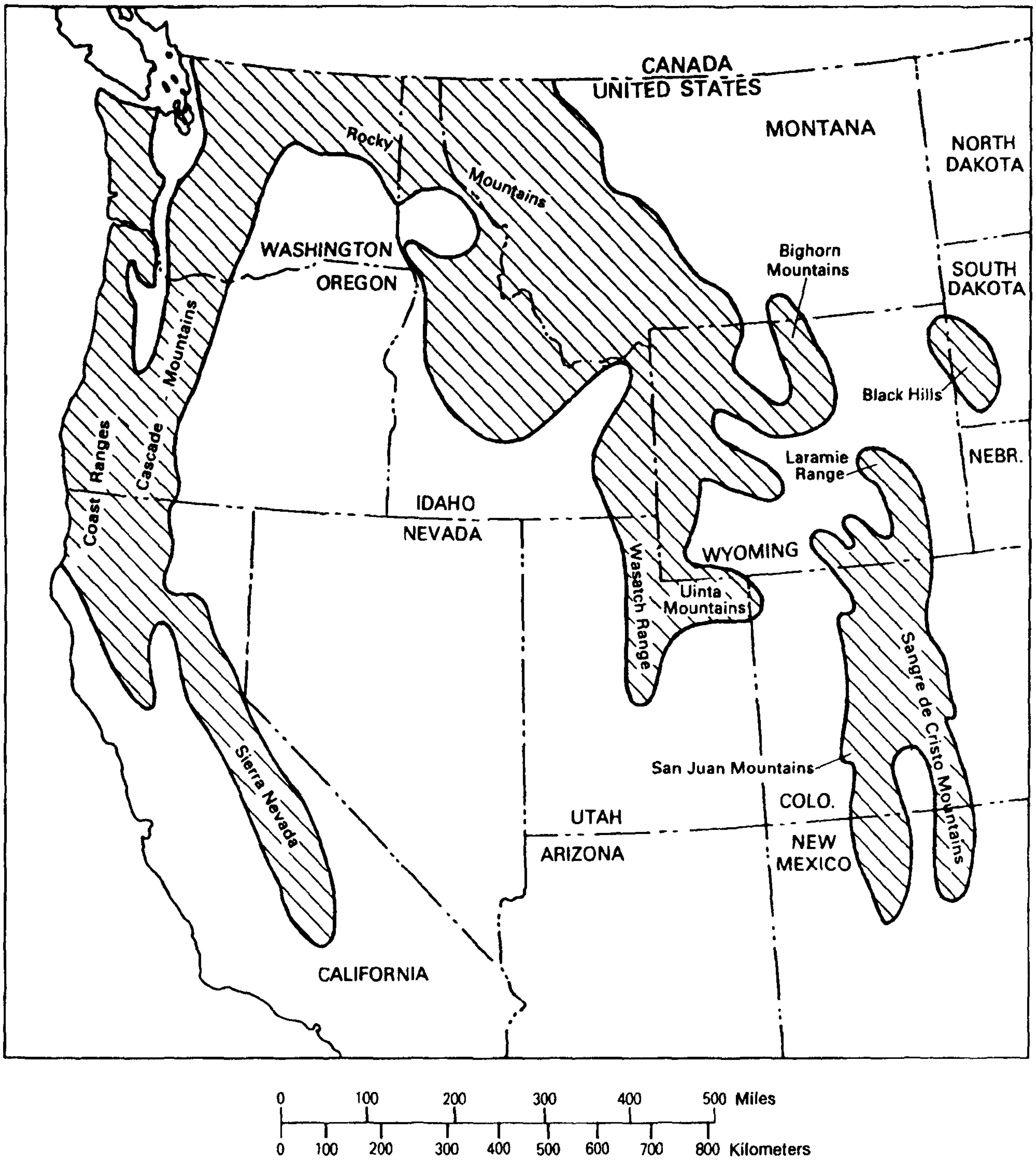

Figure 2-3. Western Mountain Ranges Region

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 feet 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 downfaulted structural troughs are underlain by moderately thick deposits of coarse-grained alluvium transported by streams from the adjacent mountains, as shown in Figure 2-4.

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 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.

The Western Mountain Ranges are sparsely populated and have relatively small water needs. The region is an exporter of water to adjacent "have-not" areas. Numerous surface reservoirs have been constructed in the region. Many such impoundments have been developed on streams that drain the western flank of the Sierra Nevada in California and the Rocky Mountains in Colorado.

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

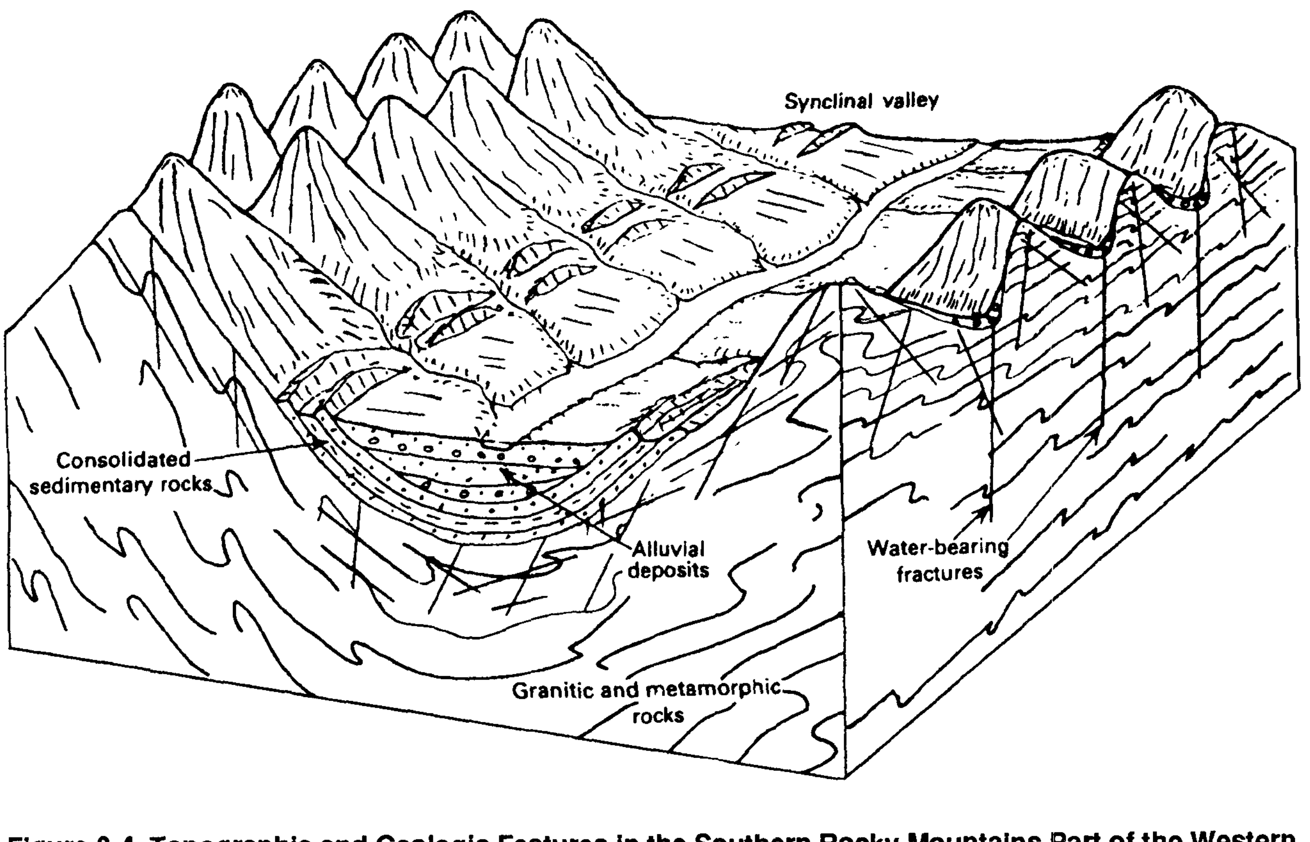

Figure 2-4. Topographic and Geologic Features in the Southern Rocky Mountains Part of the Western Mountain Ranges Region

region underlain by crystalline rocks, relatively little opportunity exists for development of ground-water supplies. The best opportunities exist in the 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 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.

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 396,000 mi^2 extending from the Puget Sound-Williamette Valley area of Washington and Oregon to west Texas. The region consists of an irregular alternation of basins or valleys and mountain ranges. In the Alluvial Basins region, basins and valleys are the dominant feature. The principal exception is the Coast Ranges of southern California which 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 evaporated or transpired.

The basins and valleys range from about 280 ft below sea level in Death Valley in California to 6,550 ft above sea level in the San Luis Valley in Colorado. The basins range in size from a few hundred feet in width and a mile or two in length to, for the Central Valley of California, as much as 50 mi in width and 400 mi in length. The crests of the mountains are commonly 3,300 to 4,900 ft 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 areas 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 feet) layer of generally unconsolidated alluvial material that partially fills the basins. Figures 2-5, 2-6, and 2-7 illustrate this dominant element. Generally, the coarsest material occurs adjacent to the mountains; the material gets progressively finer toward the centers of the basins. However, as Figure 2-6 shows, in most alluvial fans there are layers of sand and gravel that extend into the central parts 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

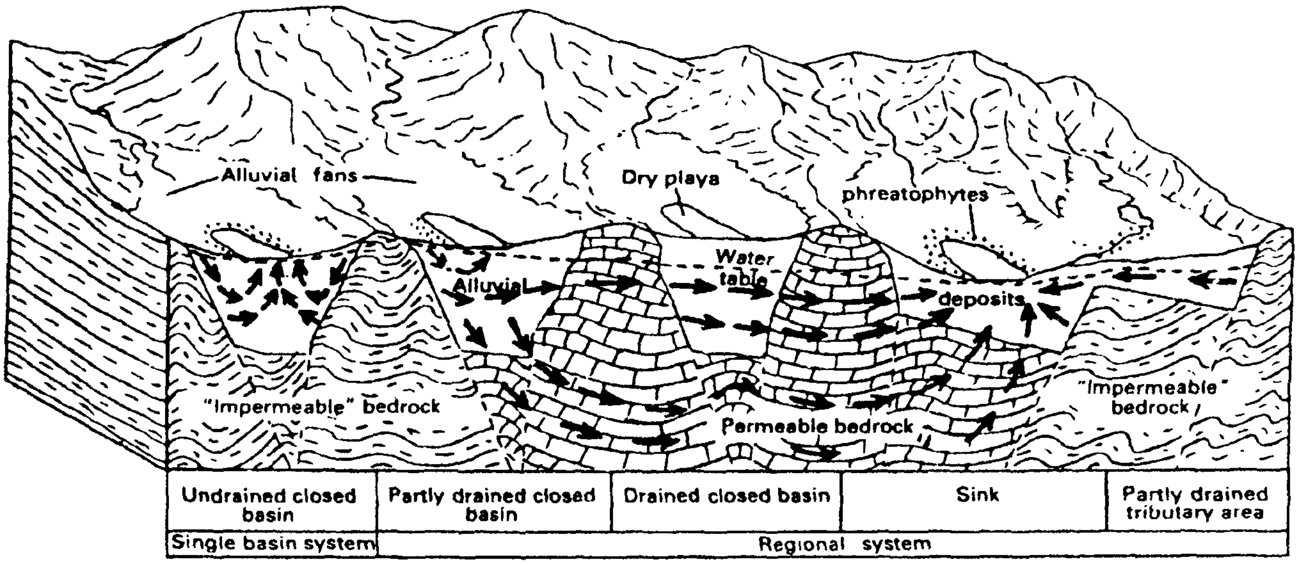

Figure 2-5. Common Ground-Water Flow Systems in the Alluvial Basins Region (From U.S. Geological Survey Professional Paper 813-G)

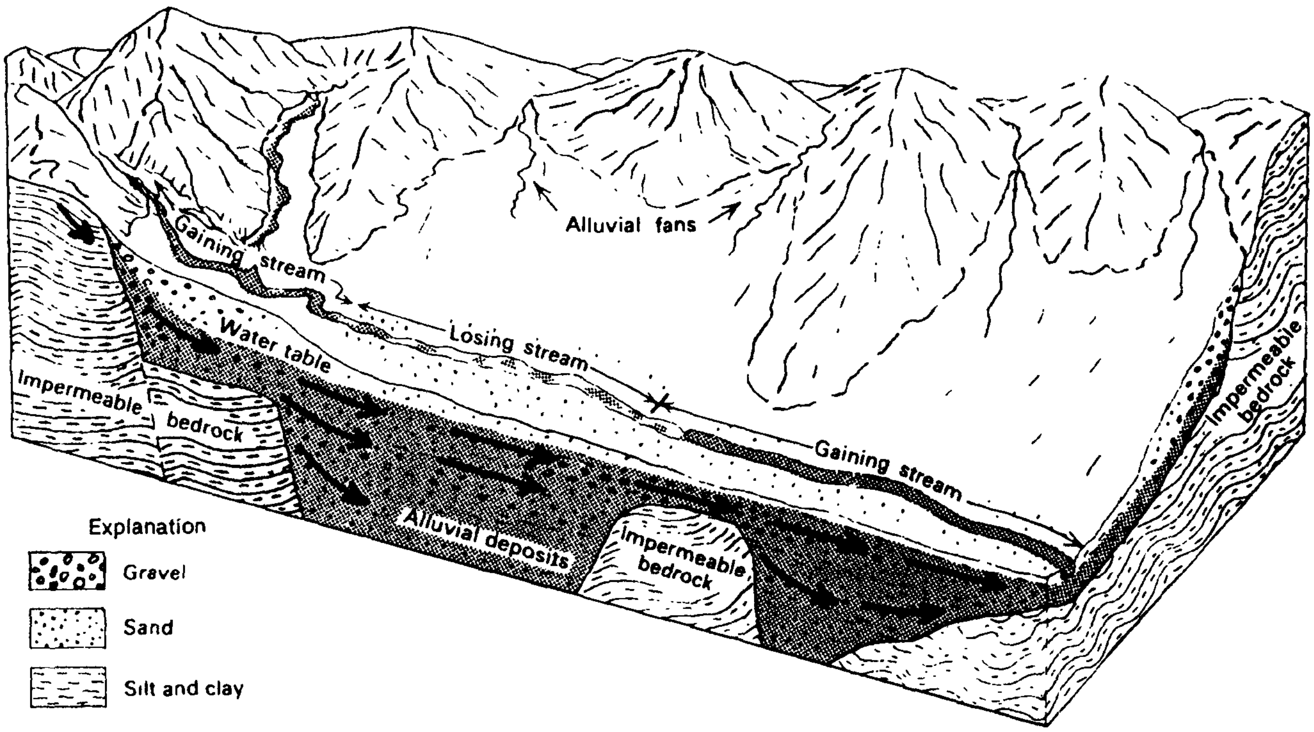

Figure 2-6. Common Relationships between Ground Water and Surface Water in the Alluvial Basins Region (Modified from U.S. Geological Survey Professional Paper 813-G)

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 Williamette 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 glacial meltwater. The gravel and sand are interbedded with clay in parts of the area. The Williamette Valley is mostly underlain by interbedded sand, silt, and clay deposited on floodplains by the Williamette 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 4 to 6 in. 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 16 in to more than 31 in. 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, precipitation runs off rapidly down the valleys and out onto the fans, where it infiltrates. 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 (playas), evaporates relatively quickly, leaving both a thin deposit of clay and other sediment and a crust of the soluble salts that were dissolved in the water, as Figure 2-5 illustrates.

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." As Figure 2-5 shows, water may move through permeable bedrock from one basin to another, arriving, ultimately, at a large playa referred to as a "sink." Water discharges from sinks not by "sinking" into the ground, but by evaporating. In those parts of the region drained by perennial watercourses 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 miles. 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.

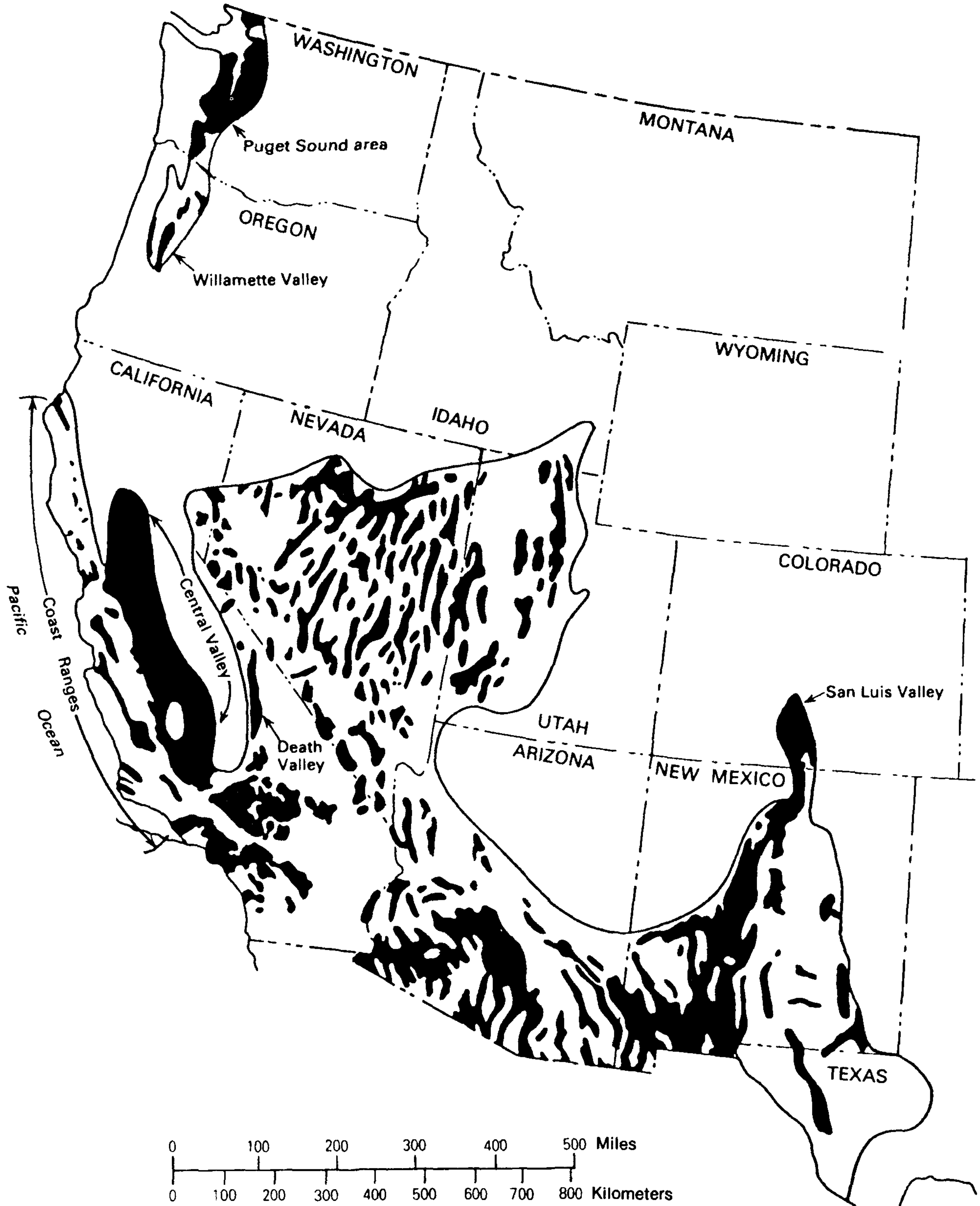

Figure 2-7. Areas Underlain by Sand and Gravel in the Alluvial Basins Region

Ground water is the major source of water in the Alluvial Basins region. Because of the dry climate, agriculture requires intensive irrigation. Most of the ground water is obtained 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 30 ft in one area, and in southern Arizona, where subsidence of more than 13 ft has been observed.

3. Columbia Lava Plateau

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

As Figure 2-8 shows, the Columbia Lava Plateau occupies an area of 141,000 mi^2 in northeastern California, eastern Washington and Oregon, southern Idaho, and northern Nevada. As its name implies, it is basically a plateau, standing generally between 1,640 and 5,900 ft above sea level, that is underlain by a great thickness of lava flows irregularly interbedded with silt, sand, and other unconsolidated deposits.

The great sequence of lava flows, which ranges in thickness from less than 160 ft adjacent to the bordering mountain ranges to more than 3,300 ft in south-central Washington and southern Idaho, is the principal water-bearing unit in the region. As Figure 2-9 shows, 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 feet to more than 160 ft and average about 50 ft. The volcanic rocks yield water mainly from permeable zones that occur at or near the contacts between some flow layers. Parts of some flows are separated by soil zones and, at places, by sand, silt, and clay. These sedimentary layers, where they occur between lava flows, are commonly referred to as "interflow sediments." Gravel, sand, silt, and clay 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: (l) 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 shown on Figure 2-8, 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 updip behind faults that are transverse to the direction of movement (Newcomb, 1962). 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 are of minor importance. This is demonstrated by conditions in the 17,000 mi^2 area of the Snake River Plain east of Bliss, Idaho.

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 3 ft to about 26 ft, account for about 10 percent of the basalt. MacNish and Barker (1976) have estimated that the hydraulic conductivity along the flow-contact zones may be a billion times higher than the hydraulic conductivity across the dense zones. The lateral extent of individual aquifers is highly variable.

The large differences in hydraulic conductivity between the 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

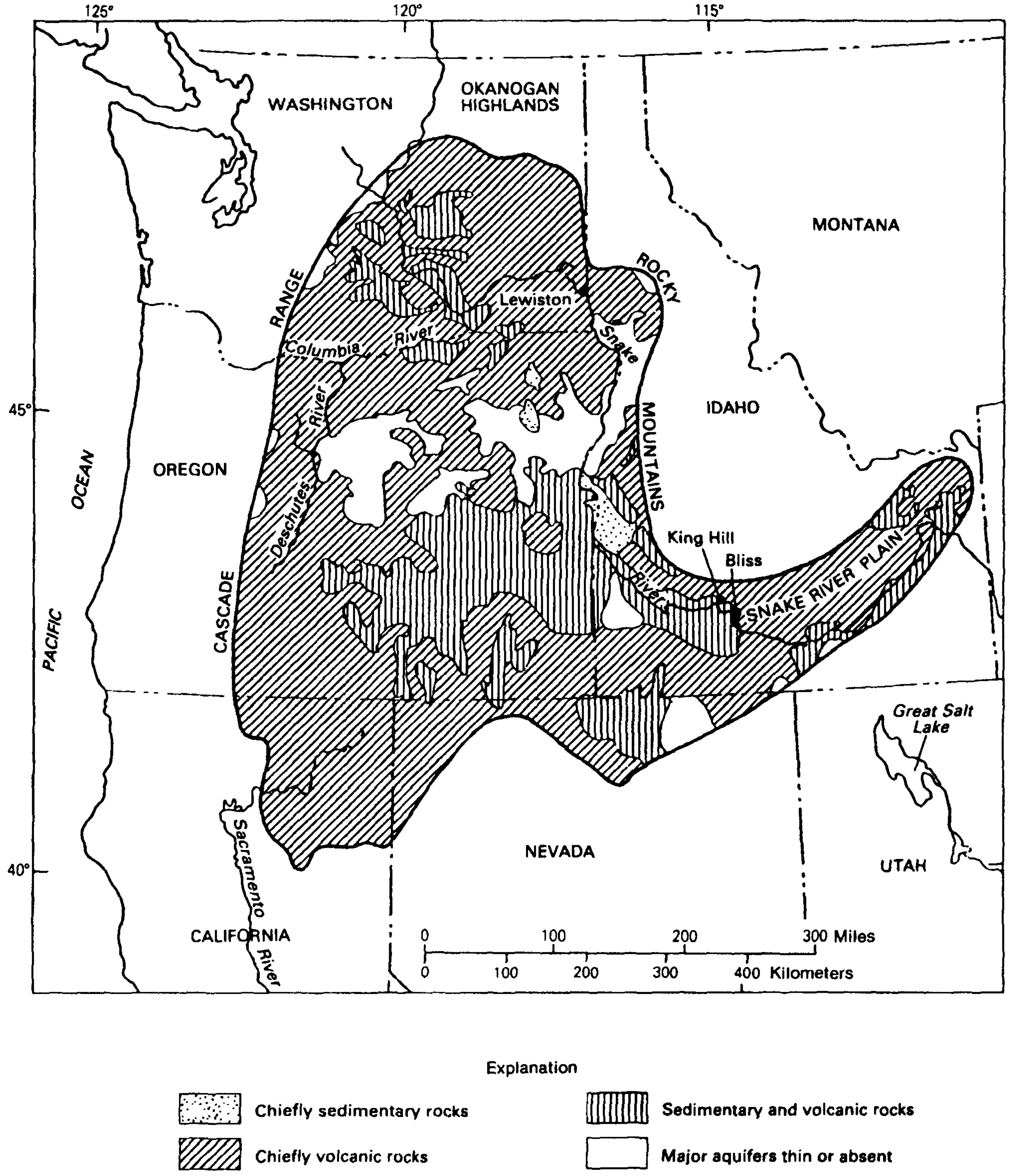

Figure 2-8. Generalized Distribution and Types of Major Aquifers of the Columbia Lava Plateau Region (Modified from U.S. Geological Survey Professional Paper 813-S)

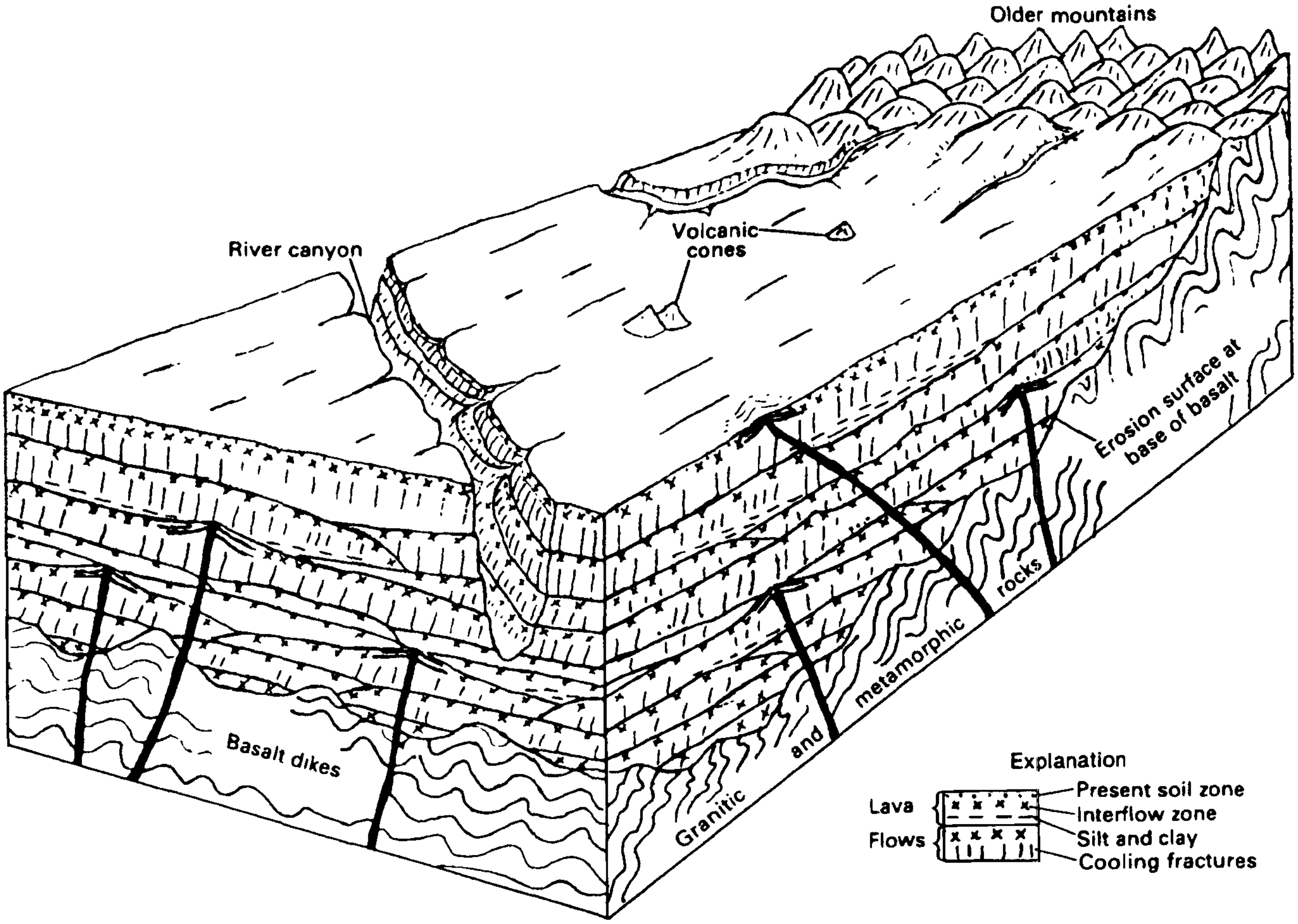

Figure 2-9. Topographic and Geologic Features of the Columbia Lava Plateau Region

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. As Figure 2-10 shows, the difference in heads between different aquifers can result in the movement of large volumes of water between aquifers through the openhole (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 8 to 47 in of precipitation annually. The areas that receive the least precipitation include the plateau area immediately east of the Cascades and the Snake River Plain. 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. The Columbia-North Pacific Technical Staff (1970) estimates that recharge may amount to 24 in 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 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 100 to 200 ft in several areas. In most of these areas, the declines have been slowed or stopped through

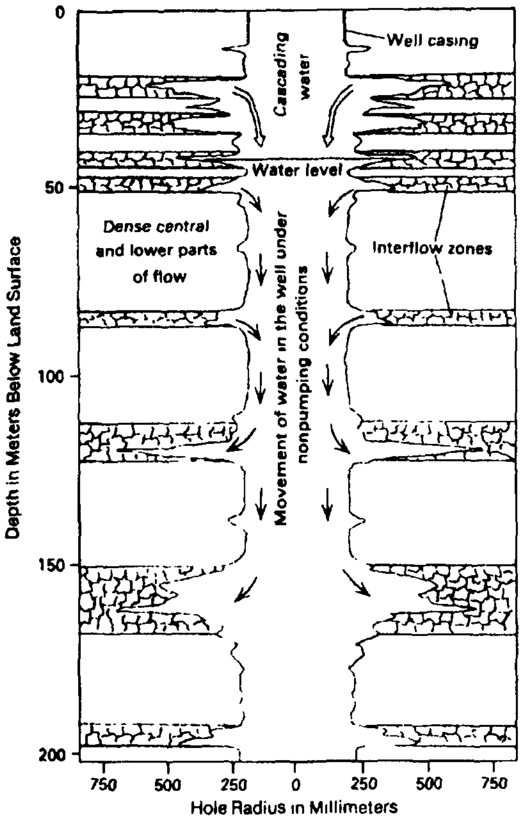

Figure 2-10. Well in a Recharge Area in the Columbia River Group (Modified from Luzier and Burt, 1974)

regulatory restrictions or other changes that have reduced withdrawals. Declines are still occurring, at rates as much as a few feet per year, in a few areas.

4. Colorado Plateau and Wyoming Basin

(Thin soils over consolidated sedimentary rocks)

The Colorado Plateau and Wyoming Basin region occupies an area of 160,000 mi^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 8,200 to 11,500 ft and underlain by horizontal to gently dipping layers of consolidated sedimentary rocks. As Figure 2-11 shows, 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. It also contains rather widely scattered extinct volcanoes and lava fields.

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

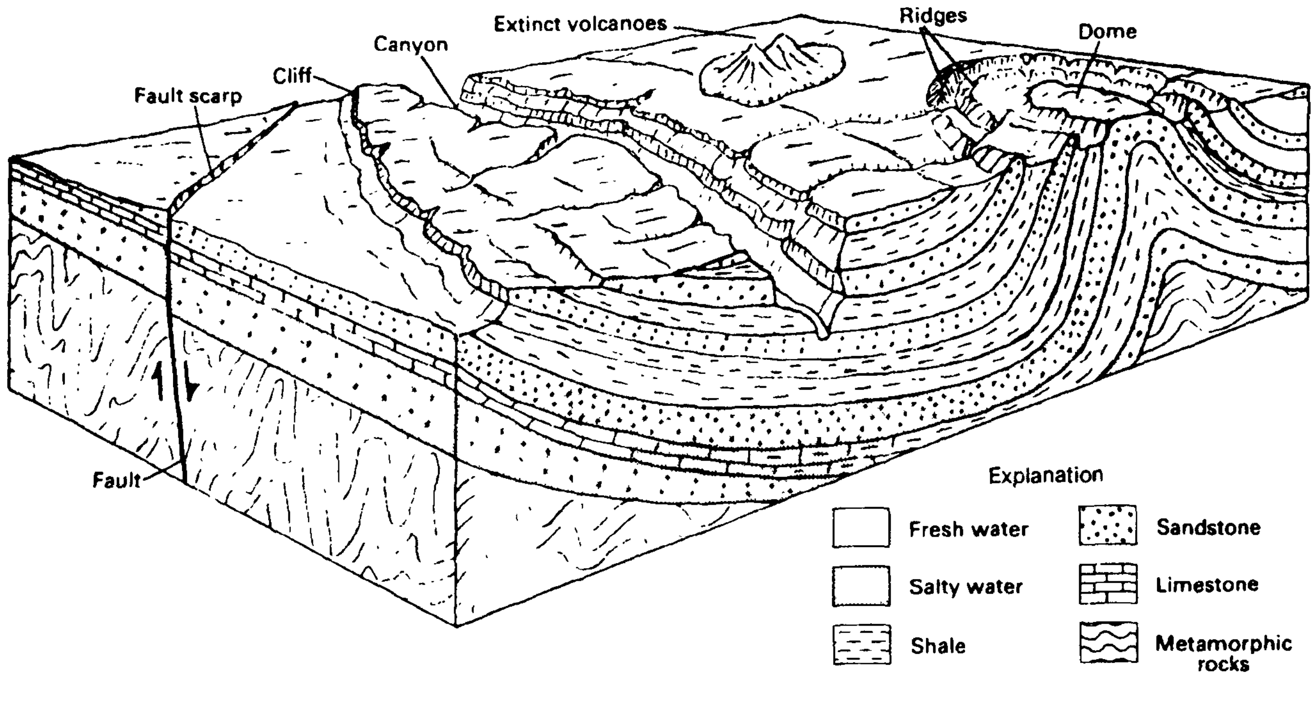

Figure 2-11. Topographic and Geologic Features of the Colorado Plateau and Wyoming Basin Region

minerals, principally halite (sodium chloride). The sandstones and shales are most prevalent and most extensive. The sandstones are the principal sources of ground water and contain water in fractures developed both along bedding planes and across the beds and in interconnected pores. The most productive sandstones are those that 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. In most of the remainder of the region there are large expanses of exposed bedrock, and the soils, where present, are thin and rocky.

Recharge of the sandstone aquifers occurs where they are exposed above the cliffs and in the ridges. Average precipitations ranges from about 6 in in the lower areas to about 39 in 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 quantity of water available for recharge is small, but so are the porosity and the transmissivity of most of the sandstone aquifers. The water in the sandstone aquifers is unconfined in the recharge areas and is confined downdip. Because most of the sandstones are consolidated, the storage coefficient in the confined parts of the aquifers is very small. Even small rates of withdrawal cause extensive cones of depression around pumping wells.

The Colorado Plateau and Wyoming Basin is a dry, sparsely populated region in which most water supplies are obtained from the perennial streams. 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 feet 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 rock, mineralized (saline) water—that is, water containing more than 1,000 mg/L of dissolved solids—is widespread. Most of the shales and siltstones contain mineralized water throughout the region and below altitudes of about 6,500 ft. 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. 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.

5. High Plains
(Thick alluvial deposits over fractured sedimentary rock)

The High Plains region occupies an area of 174,000 mi^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. Erosion 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 6,500 ft near the Rocky Mountains to about 1,600 ft 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. As Figure 2-12 shows, 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 extensively 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 tens of feet to more than 650 ft and consists of poorly sorted and generally unconsolidated clay, silt, sand and gravel.

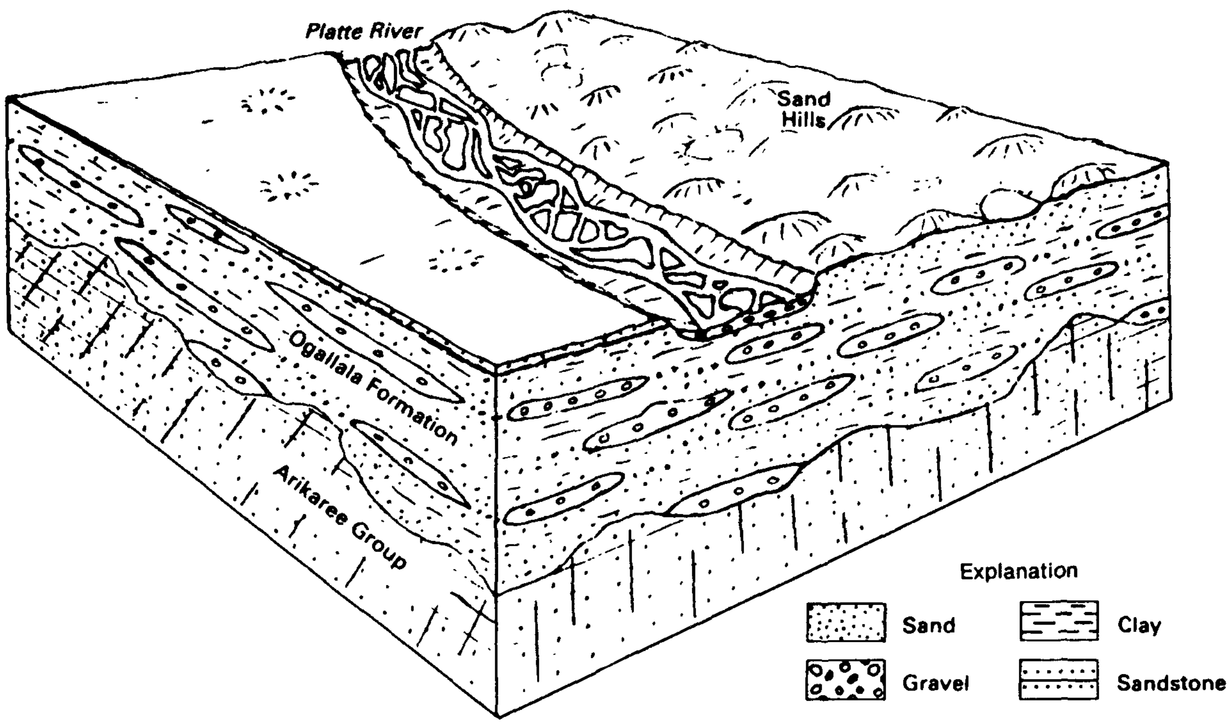

Figure 2-12. Topographic and Geologic Features of the High Plains Region

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 Quarternary deposits are composed largely of material derived from the Ogallala and consist of gravel, sand, silt, and clay. An 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 include the Arikaree Group of Miocene age and a small part of the underlying Brule Formation. The Arikaree Group 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 1000 ft, 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 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.

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 16 in along the western boundary of the region to about 24 in 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 aquifer also varies in a north-south direction. The average annual rate of recharge has been determined to range from about 0.2 in in Texas and New Mexico to about 4 in in the Sand Hills in Nebraska This large difference is explained by differences in evaporation and transpiration and by differences in the permeability of 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, with the result that most of the water evaporates. It is only during years of excessive precipitation that significant recharge occurs and this, as noted above, averages only about0.2 in per year in the southern part of the High Plains. In the Sand Hills area about 20 percent of the precipitation (or about4 in annually) reaches the water table as recharge.

Figure 2-13 shows that the water table of the High Plains aquifer has a general slope toward the east. Gutentag and Weeks (1980) estimate that, on the basis of the average hydraulic gradient and aquifer characteristics, that water moves through the aquifer at a rate of about 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 feet 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. 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 3 ft per year.

The depletion of ground-water storage in the High Plains 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 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.

6. Nonglaciated Central Region
(Thin regolith over fractured sedimentary rocks)

As Figure 2-14 shows, the Nonglaciated Central region is an area of about 671,000 mi^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 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, limestone, dolomite, and conglomerate. A small area in Texas and western Oklahoma is underlain by gypsum. Figure 2-15 shows that throughout most of the region the rock layers are horizontal or gently dipping. Principal exceptions are the Valley and Ridge section, 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. As Figure 2-16 shows, 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.

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 wind-laid deposits. In areas underlain by relatively pure limestone, the regolith consists mostly of clay and is generally only a few feet thick. Where the limestones contain chert and in the areas underlain by shale and sandstone, the regolith is thicker, up to 100 ft 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.

As Figure 2-15 shows, the principal water-bearing openings in the bedrock are fractures, which generally occur in three sets. The first set, and the one that is probably of greatest importance from the standpoint of groundwater as well yields, consists of fractures developed along bedding planes. The two remaining sets 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. The vertical fractures facilitate movement of water across the rock layers and thus serve as the principal hydraulic connection between the bedding-plane fractures.

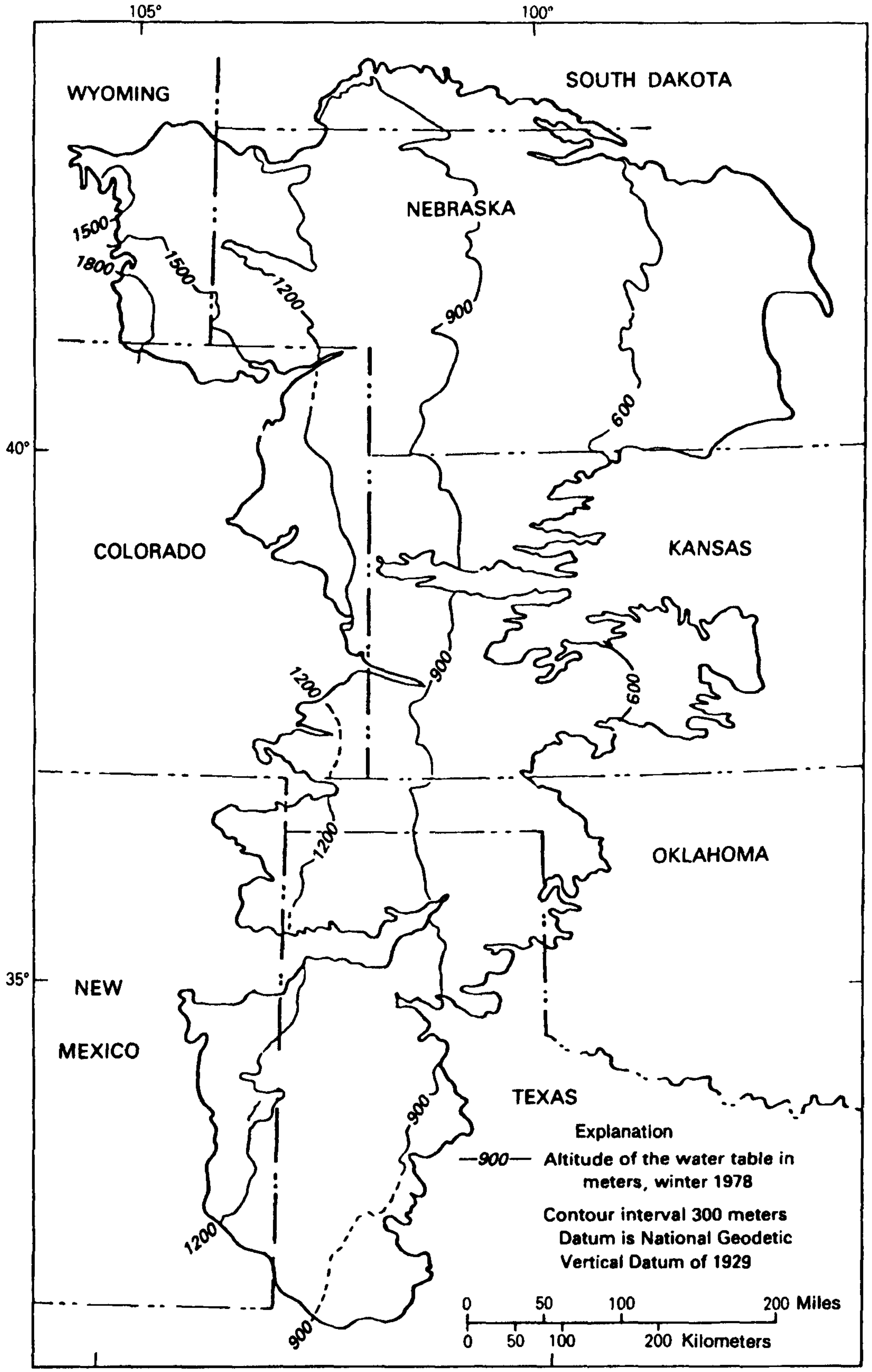

Figure 2-13. Altitude of the Water Table of the High Plains Aquifer

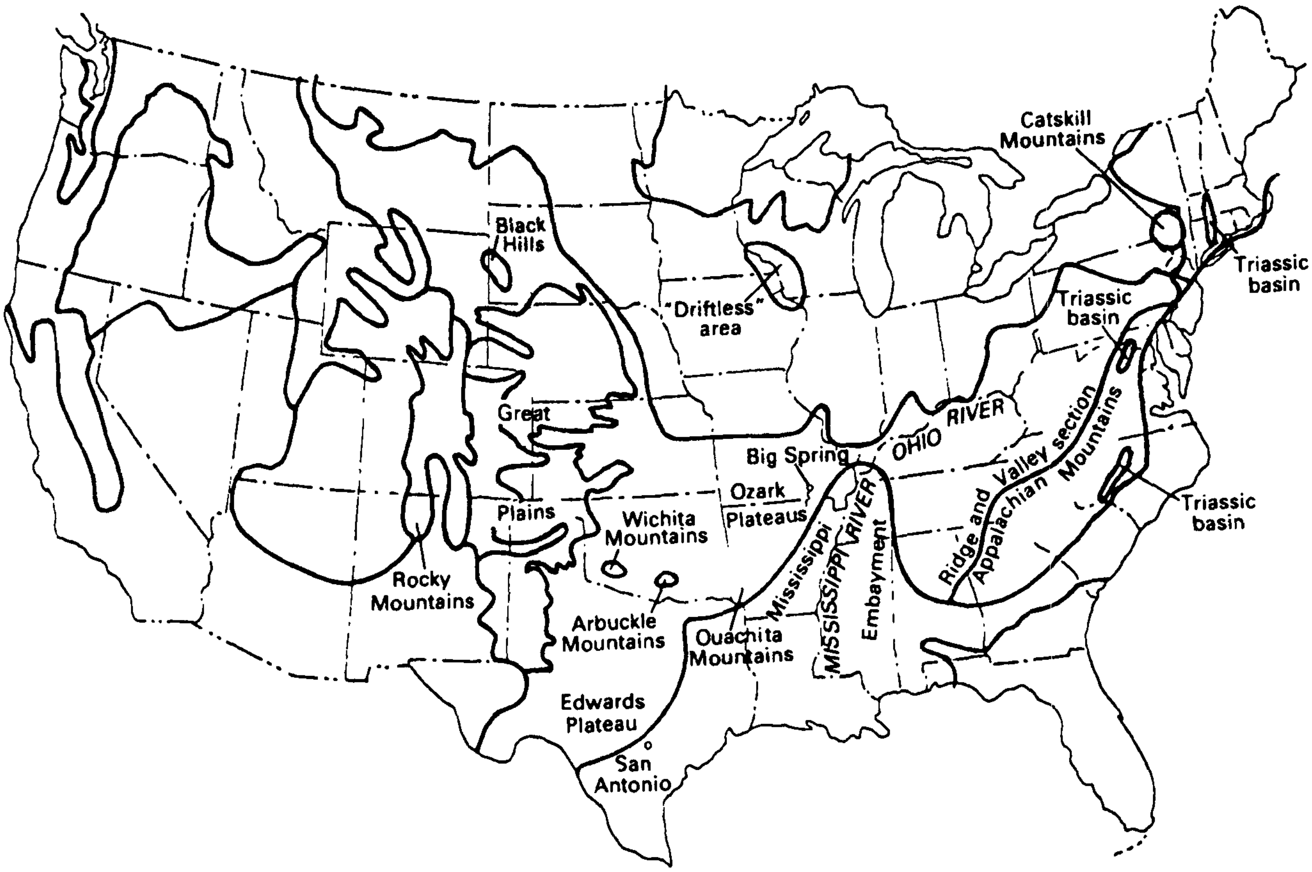

Figure 2-14. Location of Geographic Features Mentioned in the Discussions or Regions Covering the Central and Eastern Parts of the United States

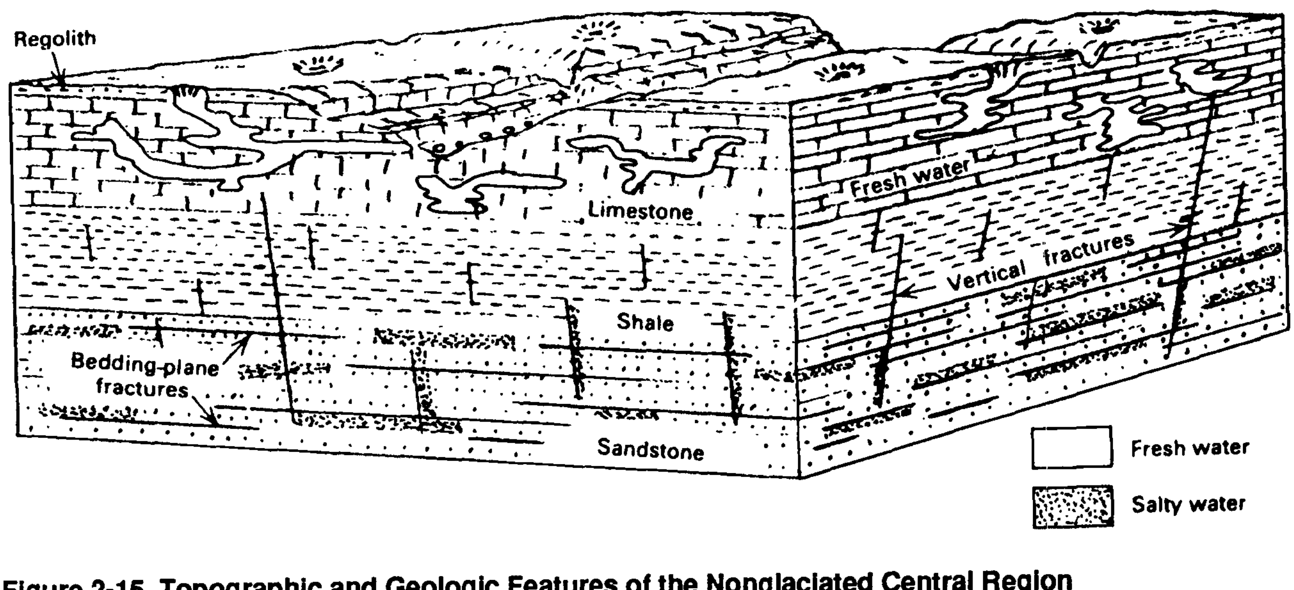

Figure 2-15. Topographic and Geologic Features of the Nonglaciated Central Region

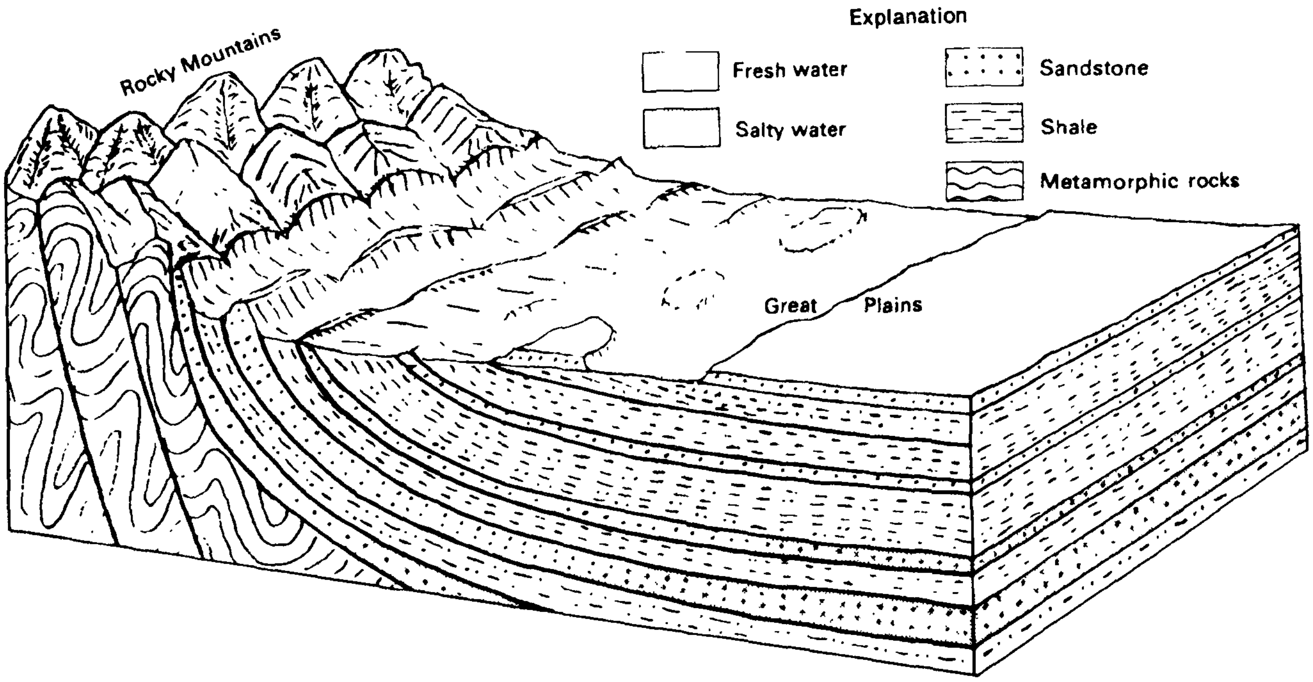

Figure 2-16. Topographic and Geologic Features Along the Western Boundary of the Nonglaciated Central Region

In the parts of the region in which the bedrock has been folded or bent, 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 a0.04 in wide. The principal exception occurs in limestones and dolomites. 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.

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 16 in per year in the western part to more than 47 in in the eastern part. This wide difference in precipitation is reflected in recharge rates, which range from about 0.2 in per year in west Texas and New Mexico to as much as 20 in 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.

The yield of wells depends on: (l) 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 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. Figure 2-14 shows the location of these areas. The Edwards Plateau in Texas is bounded on the south by the Balcones Fault Zone, in which limestone and dolomite up to 500 ft in thickness has been extensively faulted, which facilitates the development of solution openings. This zone forms 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 16,000 gallons per minute.

As Figures 2-15 and 2-16 show, 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 500 ft.

7. Glaciated Central Region
(Glacial deposits over fractured sedimentary rocks)

Figure 2-14 shows the Glaciated Central region, which occupies an area of 500,000 mi^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. Figure 2-17 shows that the Glaciated Central region is underlain by relatively flat-lying consolidated sedimentary rocks that range in age from Paleozoic to Tertiary. The bedrock is overlain by glacial deposits that, 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 feet thick. In much of the central and western parts of the region, the glacial deposits exceed 330 ft in thickness. The principal exception is the "driftless" area in Wisconsin, Minnesota, Iowa, and Illinois where the bedrock is overlain by thin soils. 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. 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. Figure 2-17 shows that the glacial deposits in buried 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.

Large parts of the region are underlain by limestones and dolomites in which fractures have been enlarged by solution. On the whole, caves and other large solution openings 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 16 in per year in the western part of the region to about

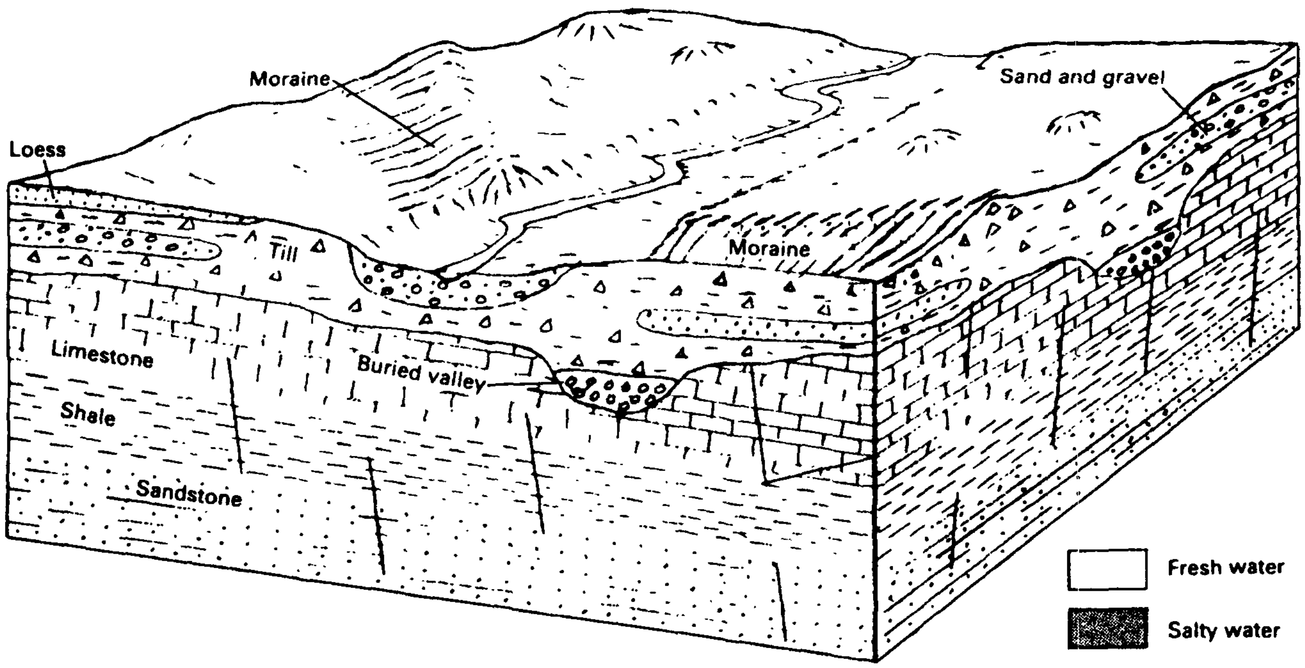

Figure 2-17. Topographic and Geologic Features of the Glaciated Central Region

39 in n the east. 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 2 in. In contrast, relatively flat areas underlain by sand and gravel may receive as much as 12 in of recharge annually in the eastern part of the region.

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

Because of the widespread occurrence of limestone and dolomite, water from both the glacial deposits and the bedrock contains as much as several hundred milligrams per liter of dissolved minerals and is moderately hard. Concentrations of iron in excess of 0.3 mg/L are a problem in water from some of the sandstone aquifers in Wisconsin and Illinois and locally in glacial deposits throughout the region. Sulfate in excess of 250 mg/L is a problem in water both from the glacial deposits and from the bedrock in parts of New York, Ohio, Indiana, and Michigan.

As is the case in the Nonglaciated Central region mineralized water occurs at relatively shallow depth in bedrock in large parts of this region. 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. At depths of 1,600 to 3,300 ft 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.

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 95,000 mi^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. The Blue Ridge is mountainous and includes the highest peaks east of the Mississippi.

The Piedmont and Blue Ridge region is underlain by bedrock of Precambrian and Paleozoic age consisting of igneous, and metamorphosed igneous, and sedimentary rocks. 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 33 to 65 ft in thickness and may be as much as 330 ft 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. While the distinction between saprolite and alluvium is not important, the term regolith is used to refer to the layer of unconsolidated deposits.

As Figure 2-18 shows 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. The hydraulic conductivities of the regolith and the bedrock are similar and range from about 0.003 to 3 ft per day. The major difference in their water-bearing characteristics is their porosities, the porosity of regolith being about 20 to 30 percent and the porosity 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-diameters 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, 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 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 terrain in which the reservoir and pipeline functions are effectively separated. Because of its larger porosity, the regolith functions as a reservoir that 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

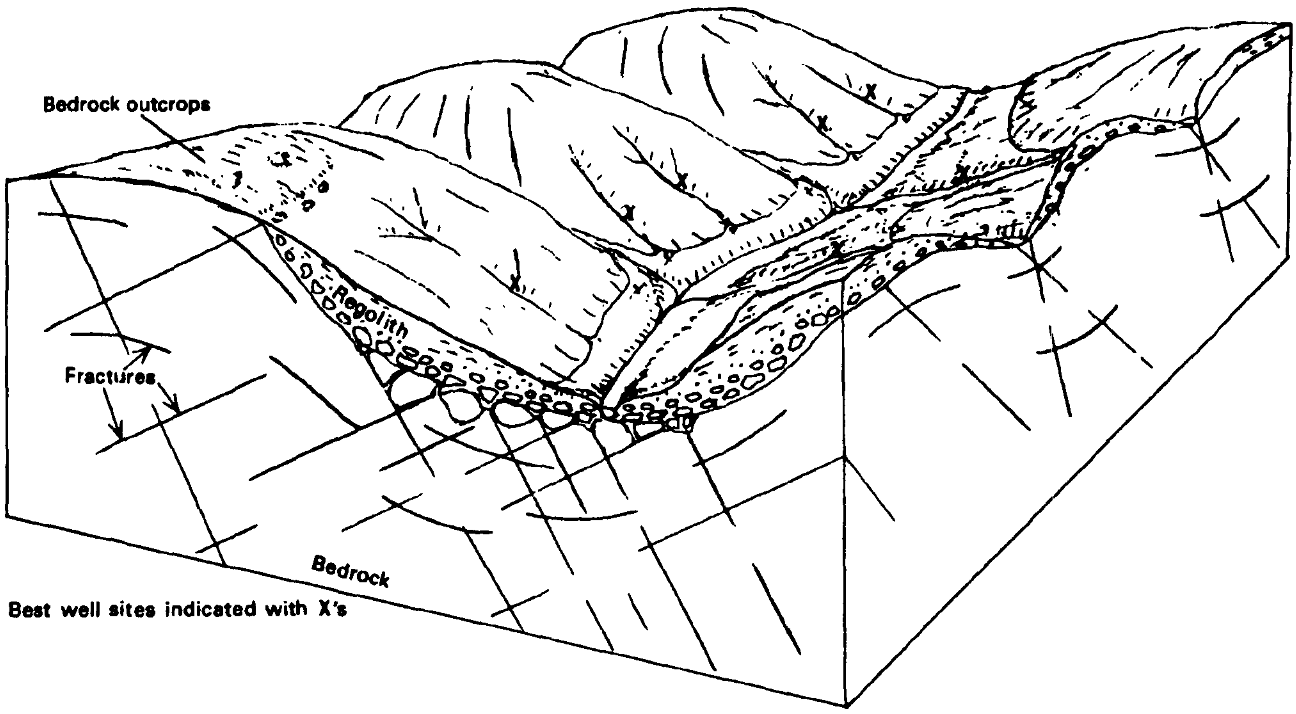

Figure 2-18. Topographic and Geologic Features of the Piedmont and Blue Ridge Region

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 and 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.

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 intensive use of ground water.

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 160,000 mi ^{2} .The Northeast Upland encompasses the Adirondack Mountains, the Lake Champlain valley, and nearly all of New England. The Superior Upland encompasses most of the northern parts of Minnesota and Wisconsin adjacent to the western end of Lake Superior.

Bedrock in the region ranges in age from Precambrian to Paleozoic, and as Figure 2-19 shows, consists mostly of intrusive igneous rocks and metamorphosed sedimentary rocks. Most have been intensively folded and cut by numerous faults.

As Figures 2-19 and 2-20 show, the bedrock is overlain by unconsolidated glacial deposits including till and gravel, sand, silt, and clay. The thickness of the glacial deposits ranges from a few feet on the higher mountains, which also have large expanses of barren rock, to more than300 ft in some valleys. The most extensive glacial deposit is till. In most of the valleys and other low areas, the till is covered by glacial outwash consisting of

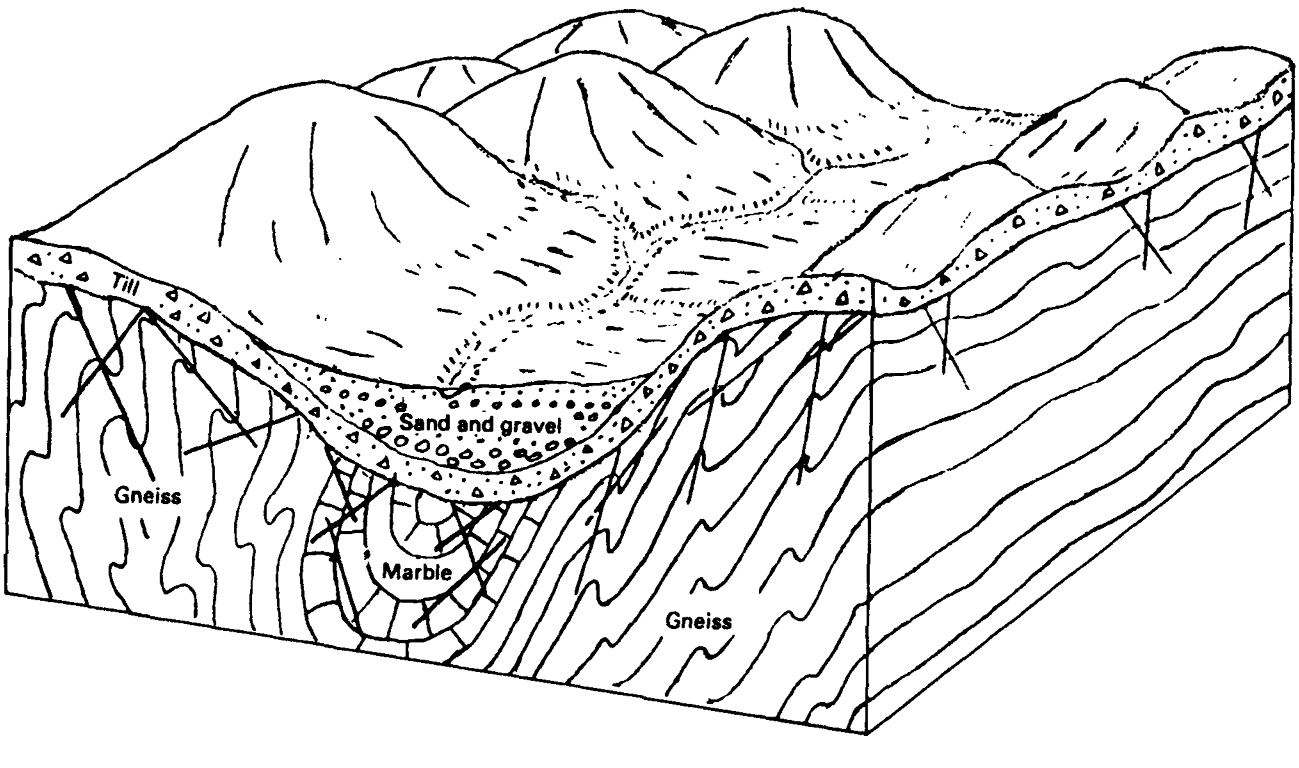

Figure 2-19. Topographic and Geologic Features of the Northeast and Superior Uplands Region.

interlayered sand and gravel, ranging in thickness from a few feet to more than 65 ft.

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 200 ft thick. Water occurs in the bedrock in fractures similar in origin, occurrence, and hydraulic characteristics to those in the Piedmont and Blue Ridge region.

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 47 in per year, is twice that on the Superior Upland, with the result that recharge is largest in the Northeast. The glacial deposits in the region serve as a storage reservoir for the fractures in the underlying bedrock.

Water supplies in the Northeast and Superior Uplands region are obtained from open-hole drilled wells in bedrock, from drilled and screened or openend 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.

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 falling on the Northeast in 1982 had a pH in the range of 4 to 6 units. Because of the low buffering capacity of the soils derived from 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

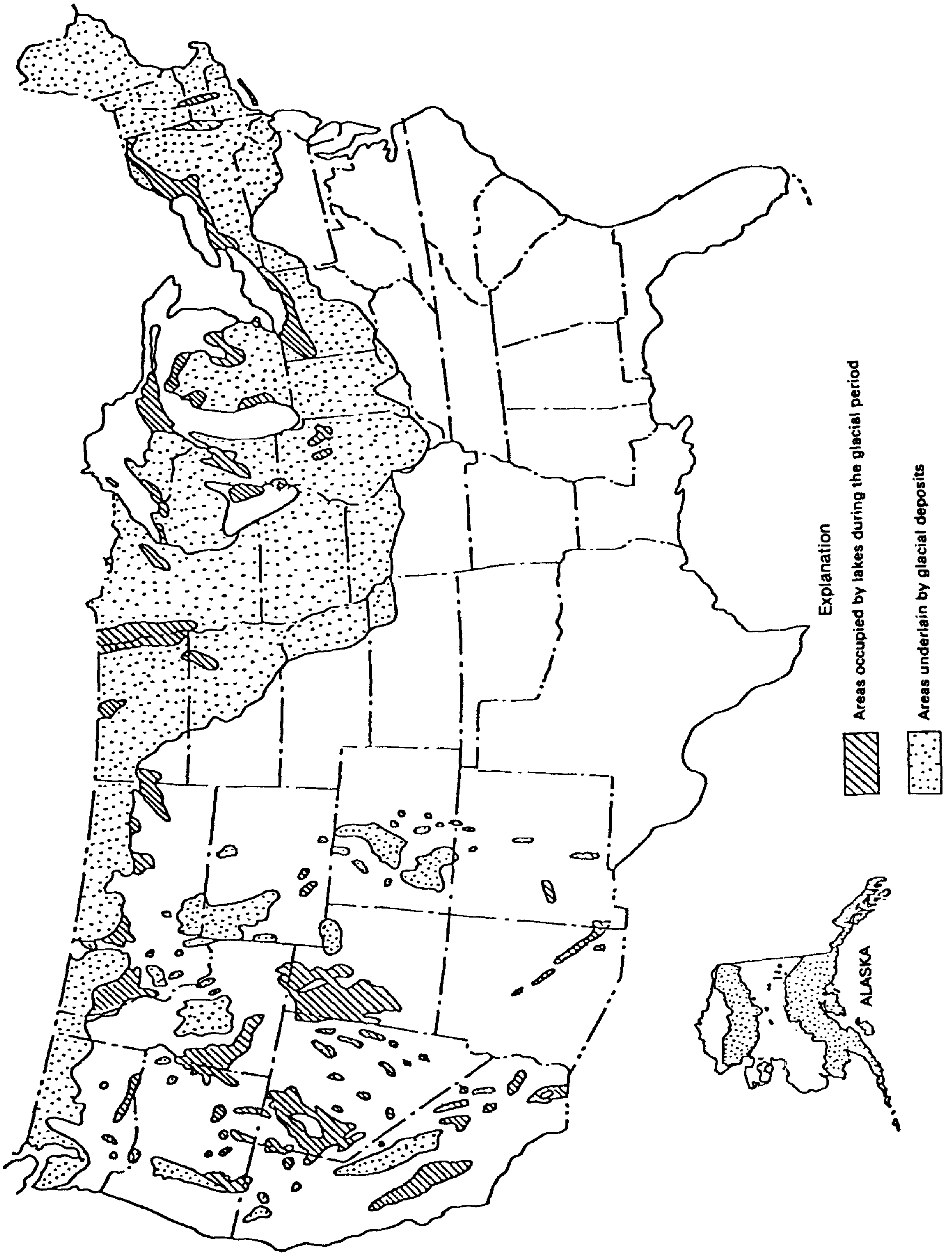

Figure 2-20. Glacial Features of the United States (Adapted from U.S. Geological Survey, 1970, p. 76)

determined. The second problem—that of de-icing salts—affects ground-water quality adjacent to streets and roads maintained for winter travel.

10. Atlantic and Gulf Coastal Plain
(Complexly interbedded sand, silt and clay)

The Atlantic and Gulf Coastal Plain region is an area of about 326,000 mi^2 extending from Cape Cod, Massachusetts, to the Rio Grande in Texas. This region does not include Florida and parts of the adjacent states.

The topography of the region ranges from extensive, flat, coastal swamps and marshes, 3 to 6 ft above sea level, to rolling uplands, 300 to 800 ft 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. These sediments, which range in age from Jurassic to the present, range in thickness from less than a foot near the inner edge of the region to more than 39,000 ft in southern Louisiana. 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 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, as shown in Figure 2-21.

Although sand, silt, and clay are the principal types of material underlying the Atlantic and Gulf Coastal Plain, there are also small amounts of gravel interbedded with the sand, a few beds composed of mollusk shells, and small amounts 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 10,000 mi^2 in eastern North Carolina, is more than 650 ft 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.

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

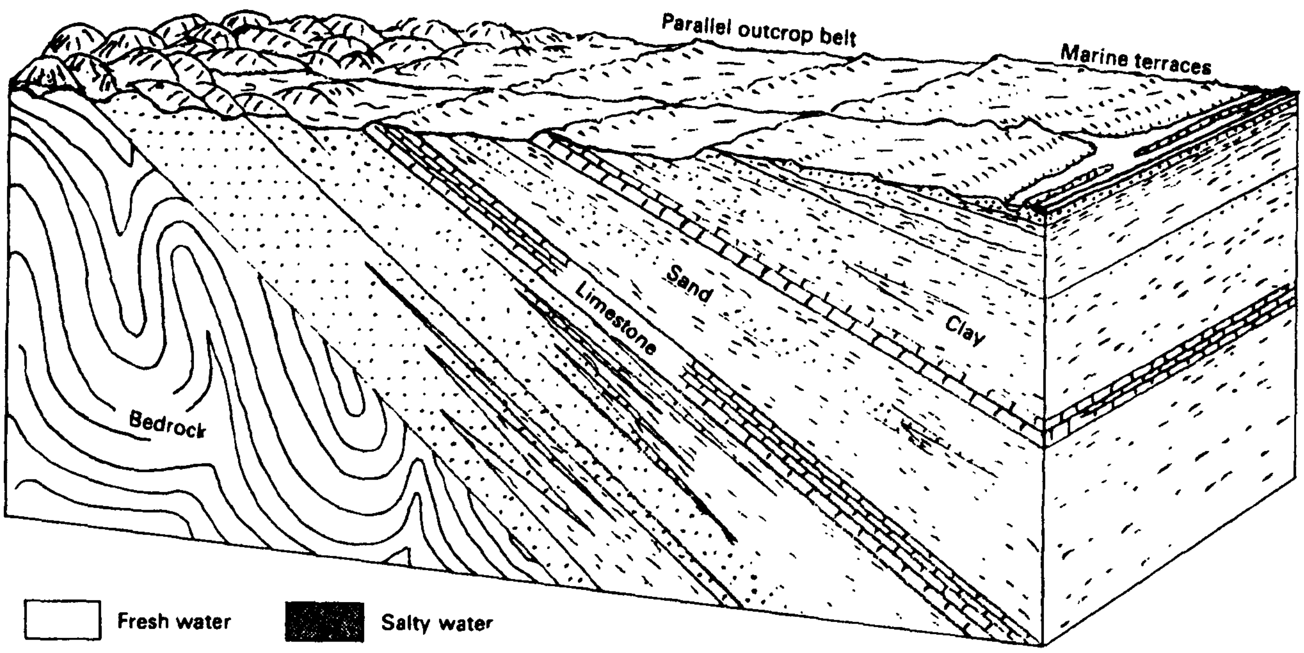

Figure 2-21. Topographic and Geologic Features of the Gulf Coastal Plain

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.

If withdrawals are continued for long periods in areas underlain by thick sequences of unconsolidated deposits, 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 30 ft as of 1978. Subsidence near pumping centers in the Atlantic Coastal Plain has not yet been confirmed but is believed to be occurring at a slower rate than along the Texas Gulf Coast.

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.

Another problem that affects ground-water development in the region concerns the presence of saline water in the deeper parts of most aquifers. 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 local problems of saltwater encroachment.

Another significant feature of the ground-water system in this region is the presence of "geopressured" zones at depths of 5,900 to 20,000 ft 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 than13,000 ft above land surface. Because the elevated temperature, natural gas, and high pressure are all potential energy sources, these zones are under intensive investigation.

11. Southeast Coastal Plain
(Thick layers of sand and clay over semiconsolidated carbonate rocks)

Figure 2-22 shows the Southeast Coastal Plain, an area of abou t 82,000 mi^2 in Alabama, Florida, Georgia, and South Carolina. It is a relatively flat, low-lying area. Much of the area, including the Everglades in southern Florida, is a nearly flat plain less than 30 ft 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. 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 formations of middle to late Miocene age or surficial deposits overlie semi-consolidated limestones and dolomites that are as much as 5,000 ft thick.

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 feet thick composed largely of loose aggregations of shells and fragments of marine organisms interbedded with much thinner layers of cement 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 18 mi 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 these aquifers underlies the southeastern part of Florida and, in the Miami area, consists of 100 to 330 ft of cavernous limestone and sand and is 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 developed in the Everglades. It is the principal source of water for municipal, industrial, and irrigation uses and can yield as much as 1,300 gal per min to small-diameter wells less than 80 ft deep finished with open holes only 3 to 6 ft long.

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

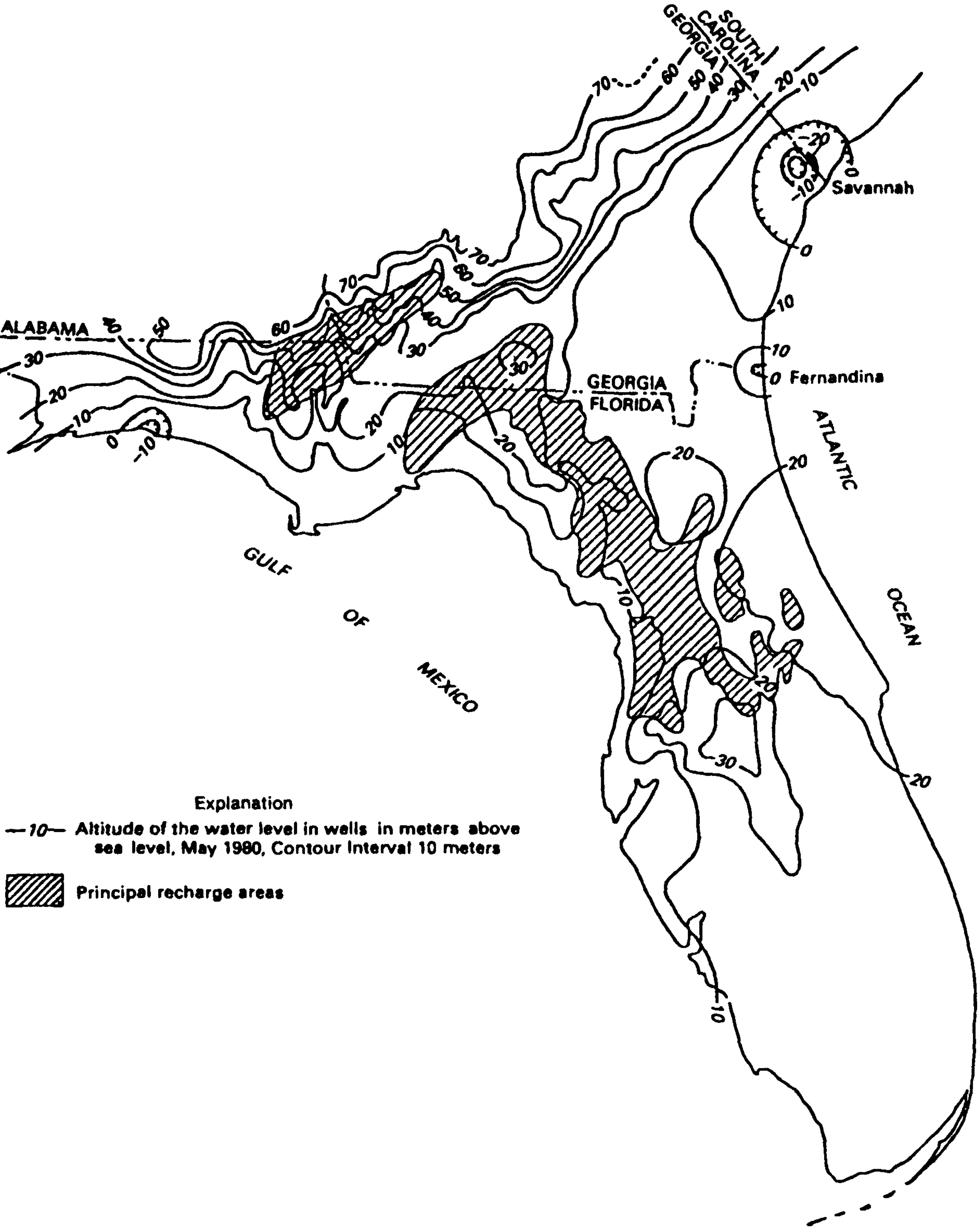

Figure 2-22. Potentiometric Surface for the Floridan Aquifer (Adapted from Johnston, Healy, and Hayes, 1981)

throughout the region and are the primary sources of ground water where the water in the Floridan aquifer contains more than about 250 mg/L of chloride.

The Floridan aquifer 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, which are shown in Figure 2-22. 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. As Figure 2-22 shows, 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 5 in. per yr. 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. Figure 2-23 illustrates this 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 feet to several miles. The larger depressions 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 wells open to the aquifer will flow at the land surface.

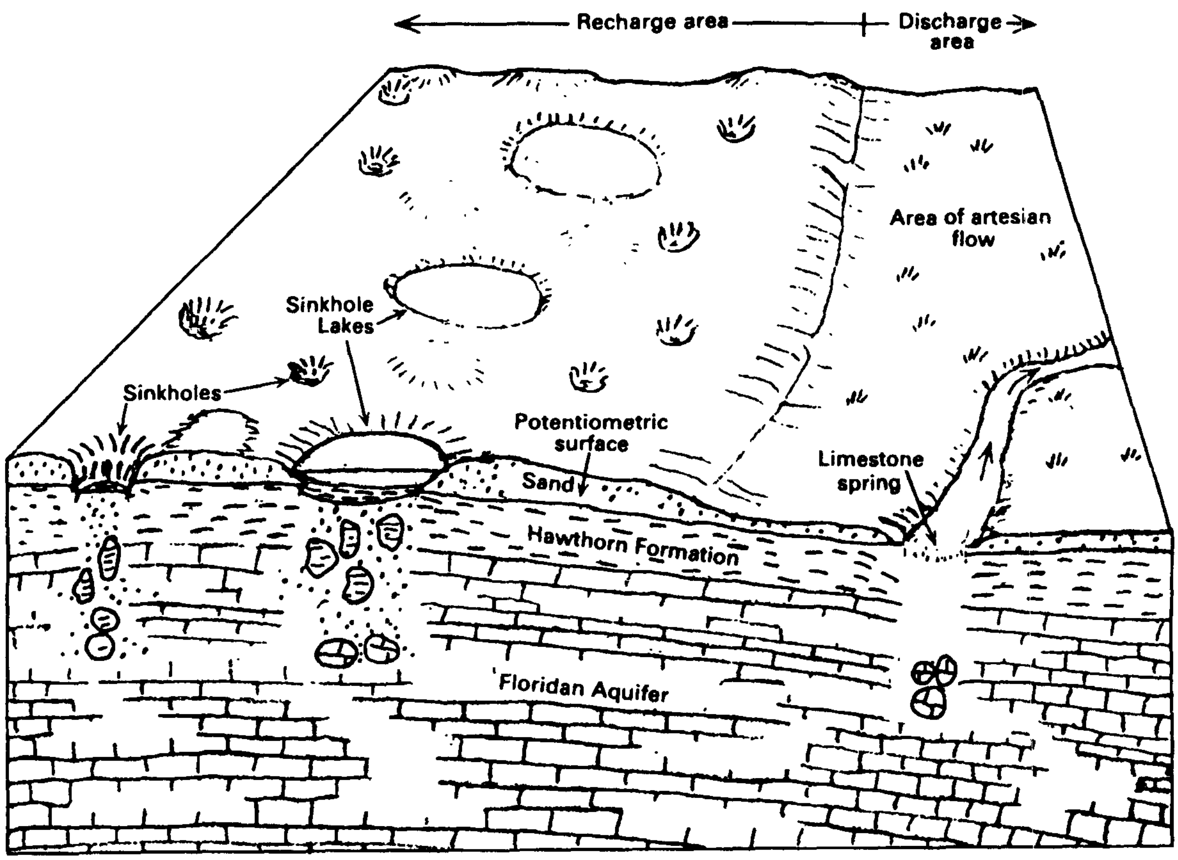

Figure 2-23. Topographic and Geologic Features of the Southeast Coastal Plain Region

The most spectacular discharge from the Floridan aquifer is through sinkholes exposed along streams and offshore.

Water supplies are obtained from the Floridan aquifer by installing casing through the overlying formations and drilling an open hole in the limestones and dolomites comprising the aquifer. Total withdrawals from the aquifer are estimated to have been about 3.5 billion gallons per day in 1978. Large withdrawals also occur from the other aquifers in the region.

12. Alluvial Valleys
(Thick sand and gravel deposits beneath floodplains and terraces of streams)

In the preceding discussions of ground-water regions, streams and other bodies of surface water were mentioned as places of ground-water discharge. In most areas ground-water systems and surface streams form a water system so intimately interconnected that a change in one causes a change in other. For example, withdrawals from ground-water systems reduce discharge to streams and thereby reduce streamflow. The movement of water from streams into ground-water systems in response to withdrawals is not a significant feature in most areas because ground-water withdrawals are dispersed over the uplands between streams rather than concentrated near them. An exception to this occurs where stream channels and floodplains are underlain by highly permeable deposits of sand and gravel. The large yields of these deposits, as well as the variability and availability of streamflow, encourage the development of these sand and gravel deposits as sources of ground water, and thus, encourage the concentration of withdrawals near streams. From the standpoint of ground-water hydrology, three criteria are used to differentiate alluvial valleys from other valleys. These criteria are as follows:

1. The alluvial valleys contain sand and gravel deposits thick enough to supply water to wells at moderate to large rates. [Commonly, the water-transmitting capacity of the sand and gravel is at least 10 times larger than that of the adjacent (enclosing) rocks.]
2. The sand and gravel deposits are in hydraulic contact with a perennial stream that serves as a source of recharge and whose flow normally far exceeds that demand from any typical well field.
3. The sand and gravel deposit occurs in a clearly defined band ("channel") that normally does not extend beyond the floodplain and adjacent terraces. In other words, the width of the deposit is small or very small compared with its length.

According to these criteria, the valleys of streams that were not affected by glacial meltwater are not considered alluvial valleys. The floodplains in these valleys are commonly underlain only by thin deposits of fine-grained alluvium. These criteria also eliminate the "buried" valleys of the glaciated area. Although the water-transmitting capacity of the sand and gravel in buried valleys may be large, the yield to wells in most of them is small because of the limited opportunity for recharge through the surrounding, less-permeable materials.

The alluvial valleys are commonly underlain, in addition to sand and gravel, by deposits of silt and clay. In many of the glaciated valleys in New York and New England the land surface is underlain by a layer of sand and gravel that ranges in thickness from 3 to 6 ft to more than 30 ft. The bottom of this deposit ranges, from one part of a valley to another, from a position above the water table to several feet below the bottom of streams. This surficial deposit of sand and gravel is commonly underlain by interbedded silt and clay which is, in turn, underlain by a discontinuous "basal" layer of sand and gravel.

The sequence of deposits in the alluvial valleys depends, of course, on the history of deposition in the valleys. Figure 2-24 shows that the sand and gravel in the valleys of major streams, such as those of the Mississippi, Missouri, and Ohio, are commonly overlain by deposits of clay and other fine-grained alluvium deposited during floods since the end of the glacial period.

Under natural conditions the alluvial deposits are recharged by precipitation on the valleys, by ground water moving from the adjacent and underlying aquifers, by overbank flooding of the streams, and, in some glacial valleys, by infiltration from tributary streams. Water in the alluvial deposits discharges to the streams in the valleys.

The layers of sand and gravel in the alluvial valleys are among the most productive aquifers in the country. They have been extensively developed as sources of water for municipalities, industries, and irrigation. Some of the gravel layers have hydraulic conductivities nearly as large as those of cavernous limestone. The large yields of the sand and gravel depend not only on their large water-transmitting capacity but also on their hydraulic connection to the streams flowing in the valleys. Large withdrawals from the deposits result in a reduction in ground-water discharge to the streams and, if large enough, cause infiltration of water from the streams into the deposits.

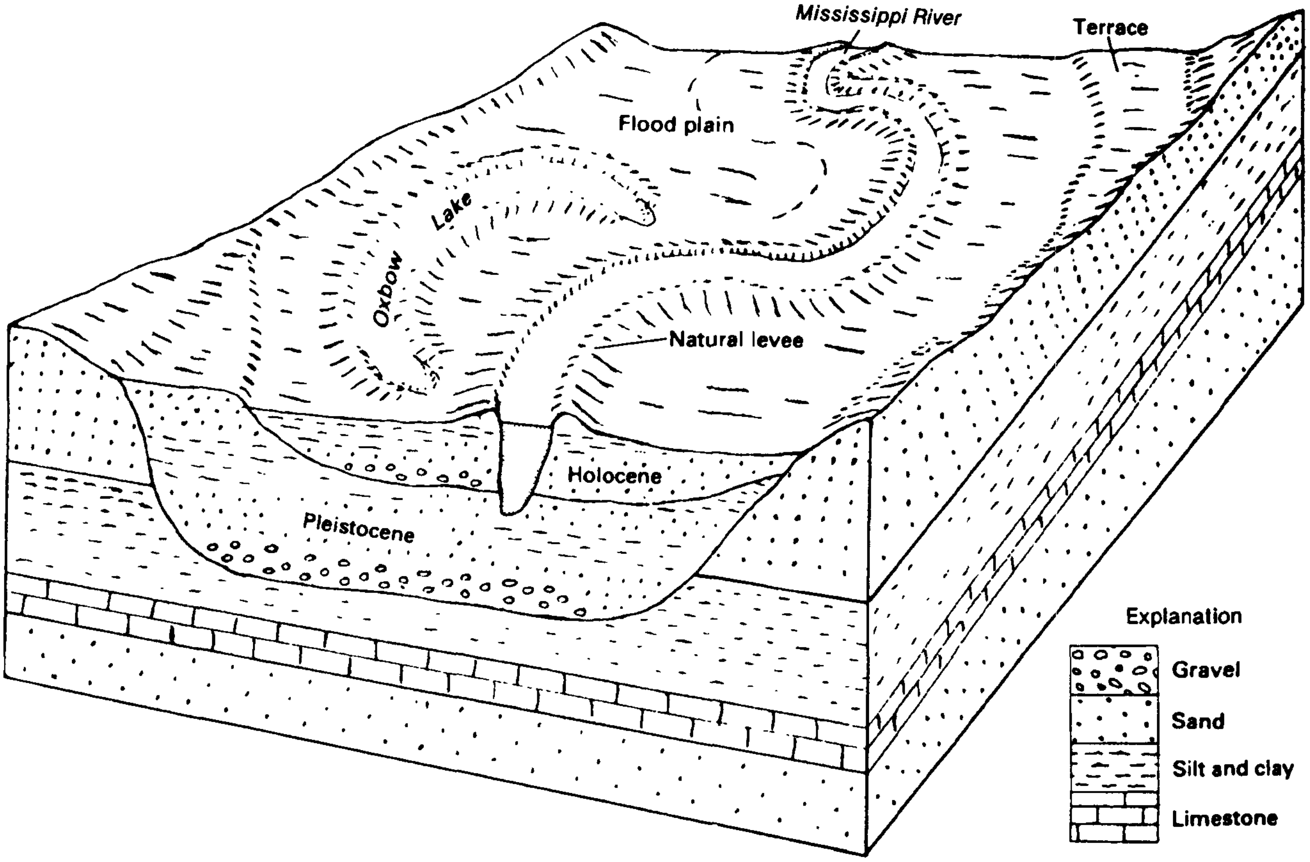

Figure 2-24. Topographic and Geologic Features of a Section of the Aluvial Valley of the Mississippi River

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Chapter 3

GROUND WATER-SURFACE WATER RELATIONSHIP

Introduction

The interrelations between ground water and surface water are of great importance in both regional and local hydrologic investigations and a wide variety of information can be obtained by analyzing streamflow data. Most commonly the surface water investigator deals with stream hydrographs, channel characteristics, geomorphology, or flood routing. Although the hydrogeologist may evaluate induced infiltration into a streamside aquifer, he is generally more interested in aquifer characteristics, such as hydraulic conductivity, thickness, boundaries, and well yields. Many hydrologists tend to ignore the fact that, at least in humid areas, ground-water runoff accounts for a significant part of a stream's total flow.

Evaluation of the ground-water component of runoff can provide important and useful information regarding regional recharge rates, aquifer characteristics, and ground-water quality, and can indicate areas of high potential yield to wells. The purpose of this chapter is to describe a number of techniques that can be used to evaluate runoff to obtain a better understanding and evaluation of ground-water resources. In particular, the following will be examined:

1. Ground-water runoff
2. Surface runoff
3. Regional ground-water recharge rates
4. Determination of areas of relatively high permeability or water-yielding characteristics
5. Determination of the background concentration of ground-water quality
6. Estimation of evapotranspiration
7. Determination of the percentage of precipitation that is evaportranspired, becomes ground-water runoff, or becomes surface-water runoff.

The approaches taken, admittedly some highly subjective, are based on: (l) short-term runoff events, (2) long-term hydrographs, and (3) dry-weather flow measurements. In the first approach a single event, such as a flood wave of a few hours or few days duration, can be analyzed, while the latter two approaches are based on annual stream hydrographs, flow-duration curves, or seepage runs. Short-term events may provide a considerable amount of information for a local area, while long-term events are most useful for regional studies. Streamflow may consist of several components including ground-water runoff, surface runoff, effluent, and precipitation that falls directly into the channel.

The volume of water that is added by precipitation directly into the channel is relatively small compared to the stream's total flow. The contribution by waste effluent may or may not be significant, since it depends on the activities that are occurring in the basin. In permeable basins in humid regions, ground-water runoff may account for 70 or 80 percent of the stream's annual discharge. The remainder is surface runoff, which originates as precipitation or snow melt that flows directly into the stream channel. This chapter is concerned largely with ground-water runoff and surface runoff and the separation of these two components.

In order to fully appreciate the origin and significance of ground-water runoff, it is first necessary to examine the regional ground-water flow system. Figure 3-1 illustrates a typical flow pattern. Particularly in humid and semi-arid regions, the water table generally conforms with the surface topography. Consequently, the hydraulic gradient or water table slopes away from divides and topographically high areas toward adjacent low areas, such as streams and rivers. Topographic highs and lows, therefore, serve as recharge and discharge areas, respectively.

Ground-water flow systems may be local, intermediate, or regional. As these terms imply, ground-water flow paths may be short, amounting to a few yards at one

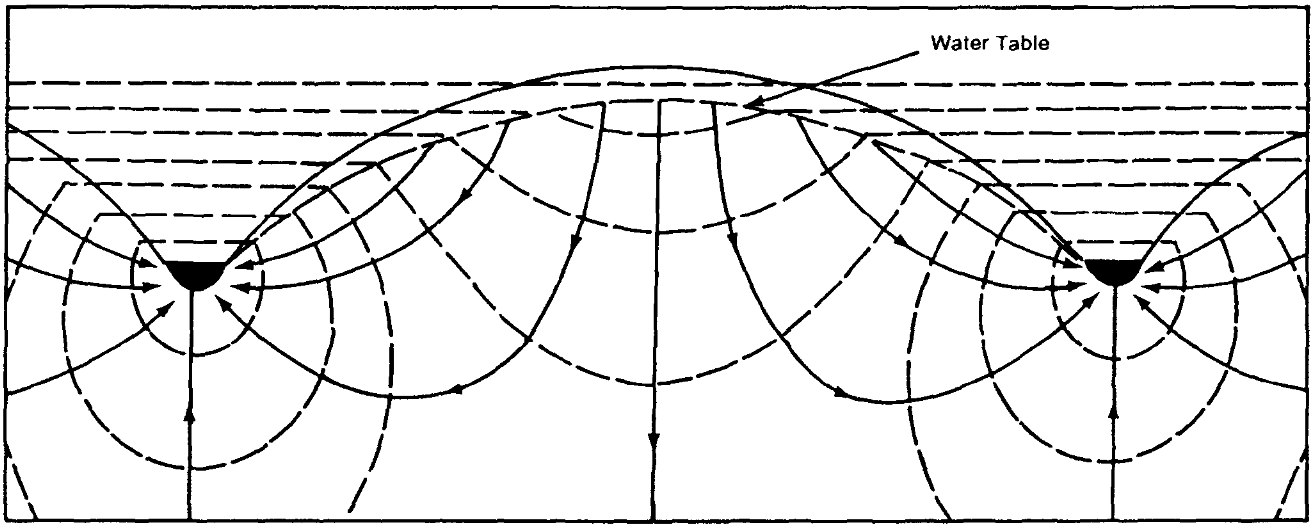


Figure 3-1. Approximate Flow Pattern in Uniformly Permeable Material between the Sources Distributed over the Air-Water Interface and the Valley Sinks (After Hubbert, 1940)

extreme to many miles in the regional case. Individual flow lines are, of course, influenced by the stratigraphy and, in particular, are controlled by hydraulic conductivity.

As water infiltrates a recharge area, the mineral content is relatively low. The quality changes, however, along the flow path and dissolved solids, as well as several other constituents, generally increase with increasing distances traveled in the subsurface. It is for this reason that even nearby streams may be typified by different chemical quality. A stream, seep, or spring in a local discharge area may be less mineralized than that issuing from a regional discharge zone because of the increase in mineralization that takes place along longer flow paths. It must be remembered, however, that other conditions, such as soil type, solubility of the enclosing rocks, surface drainage characteristics, and waste disposal practices, may have a profound effect on water quality at any particular site.

Even streams in close proximity may differ considerably in discharge even though the size of the drainage area and climatic conditions are similar. Figure 3-2 gives the superimposed hydrographs of White River in southwestern South Dakota and the Middle Loup River in northwestern Nebraska, which are good examples. White River has a low discharge throughout most of the year, but from May to September, flash floods are common. The wide extreme in discharge is characteristic of a flashy stream.

The flow of Middle Loup River is nearly constant, although from late spring to early fall higher flows may occur. These peaks, however, differ considerably from those found in White River because the increase in discharge takes place over a longer interval, the stage does not range widely, and the recession occurs more slowly. The differences in hydrographs of these two nearby rivers is puzzling, until the geology and topography of their respective basins are examined.

White River flows through the Badlands of South Dakota, an area of abrupt changes in relief, steep slopes, little vegetative cover, and rocks that consist largely of silt and clay, both of which may contain an abundance of bentonite. When wet, bentonite, a swelling clay, increases greatly in volume. As a result of these features, rainfall in the White River basin tends to quickly run off and there is little opportunity for infiltration and ground-water recharge to occur. Thus, intense rainstorms cause flash floods, such as those that occurred in June, August, and September.

The Middle Loup basin is carved into the undulating grassland topography of the Sandhills of Nebraska, where surficial materials consist of wind-blown sand. Since the low relief, grass-covered surface promotes infiltration, precipitation is readily absorbed by the underlying sand. As a result, there is very little surface runoff and a great amount of infiltration and ground-water recharge. The ground water slowly migrates to the river channel, thus providing a high sustained flow. In a comparison of the hydrographs of these two rivers, it is evident that the geologic framework of the basin

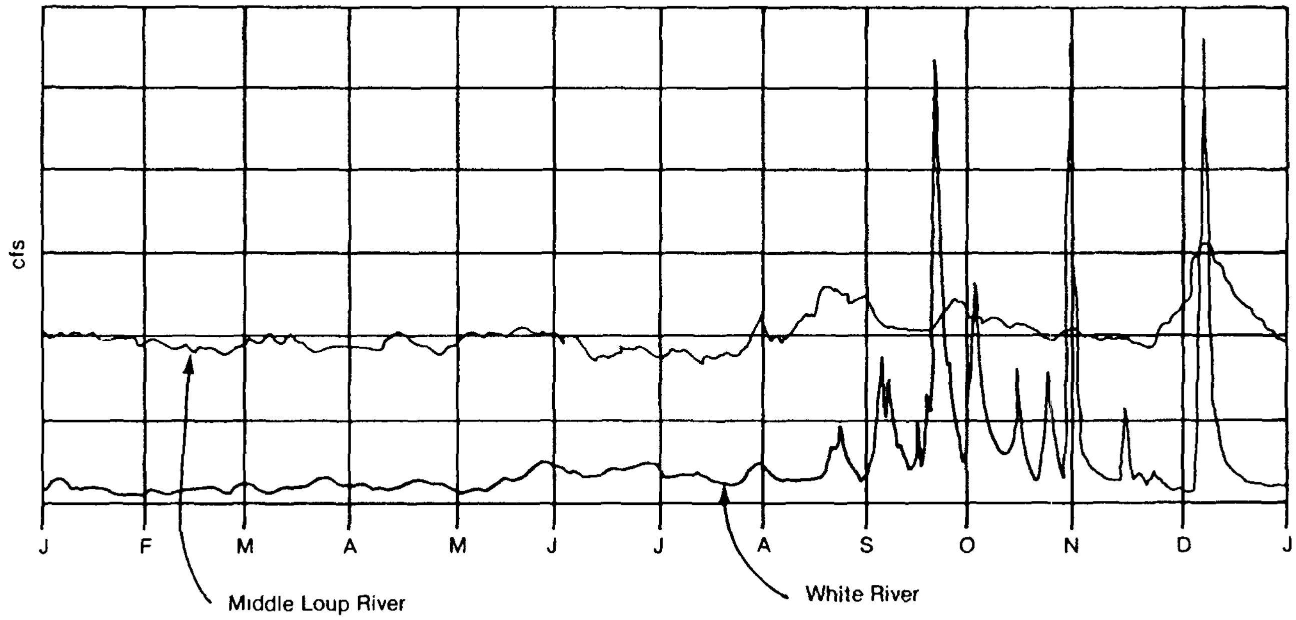


Figure 3-2. Hydrographs of Two Nearby Streams

serves as a major control on runoff. This further implies that in any regional hydrologic study, the investigation should begin with an examination of geologic maps.

Gaining and Losing Streams

Although the discharge of most streams increases downstream, the flow of some streams diminishes. These streams are referred to as gaining or losing, respectively. The hydrologic system, however, is even more complex, because a stream that may be gaining in one season, may be losing during another. Furthermore, various human activities may also affect a stream's discharge.

Under natural conditions a gaining stream is one where the water table is above the base of the stream channel. Of course the position of the water table fluctuates throughout the year in response to differences in ground-water recharge and discharge. Normally the water table is highest in the spring, which is the annual major period of ground-water recharge. From spring to fall, very little recharge occurs and the amount of ground water in storage is slowly depleted as it seeps into streams. Eventually, the water table may decline to the same elevation as a stream bottom, or even below it, at which time streamflow ceases except during periods of surface runoff. Following a period of recharge, caused either by infiltration of rainfall or seepage from a flood wave, the water table may again rise and temporarily contribute ground-water runoff.

Figure 3-3 shows a generalized diagram of the hydrology of a stream during two seasons of the year. During the spring, the water table is high and the gradient dips steeply towards the stream. If streamflow was measured at selected points, it would be found that the discharge increases downstream because of the addition of ground-water runoff. That is, it is a gaining stream. In the fall when the water table lies at or below the stream bottom, however, the same stream might become a losing stream. During a major runoff event the stage in the stream would be higher than the adjacent water table and water would migrate from the stream into the ground. The stream would continue to lose water until the water table and river stage were equal. When the stage declined, ground-water runoff would begin again.

In this case the stream changed from gaining to losing and back again to gaining. Similar situations may occur over longer intervals, such as during droughts. As a drought continues, the water table slowly declines as ground-water storage is depleted. A period of high flows, such as release from a dam, may cause tremendous amounts of water to flow from the stream channel into the ground, thus saturating the depleted streamside deposits. It may require weeks of high flow to replenish the ground-water reservoir, and until this is accomplished, the stream will be losing.

Some streams, particularly in arid and karst regions, are nearly always losing. Examples include those channels that cross coarse-grained alluvial fans. Even during

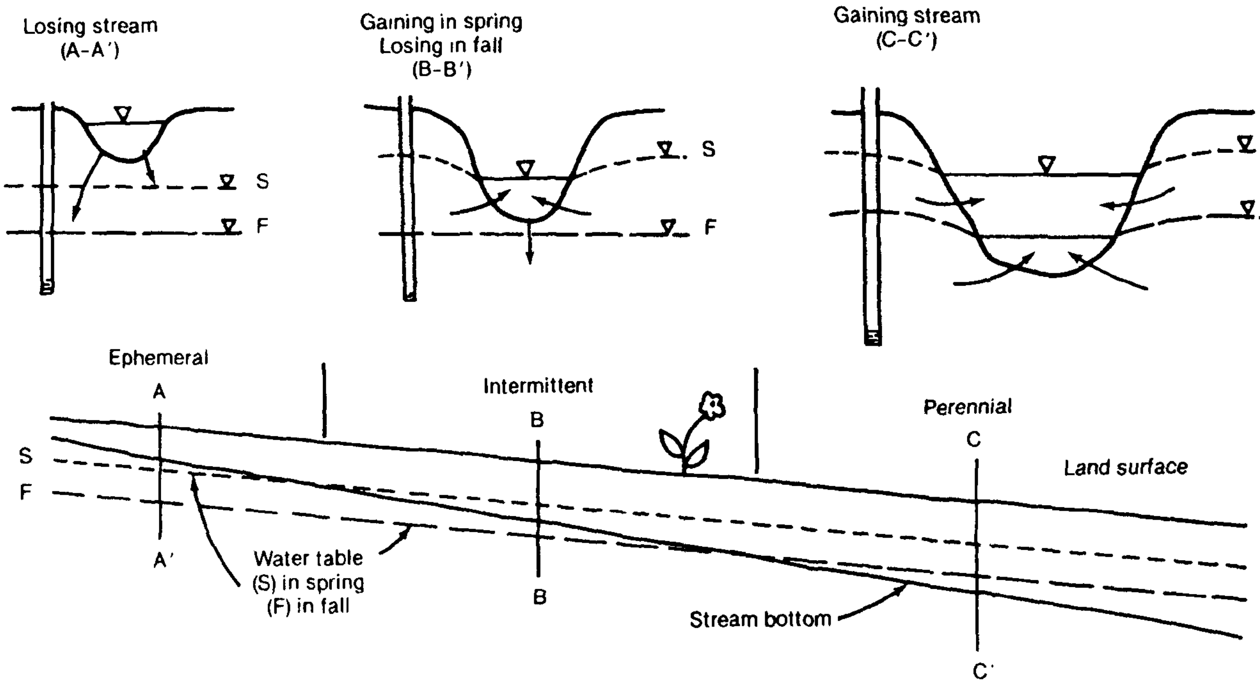


Figure 3-3. The Relation between the Water Table and Stream Types

flash floods, the great mass of flood water soon spreads out over the fan or adjacent desert to infiltrate or evaporate.

Because of the extensive network of solution openings in karst terrain, the water table may consistently lie below the bottom of all the streams. During a period of runoff, the water may rapidly flow into sink holes and solution openings or simply disappear into a swallow hole in a stream channel, only to appear again perhaps several miles downstream.

Gaining and losing streams also can be created artificially. Where well fields lie along stream channels and induce water to flow from the stream to the well, streaflow is diminished. In some cases stream depletion by pumping wells has proceeded to such an extent that the stream channels are dry throughout the year. Conversely, in some irrigated regions, so much infiltration occurs that the water table rises to near land surface. The underlying soil and ground water may become highly mineralized by the leaching of soluble salts. These highly mineralized waters may discharge into a stream, increasing its flow but deteriorating the chemical quality. In other places, municipal or industrial wastes may add considerably to a stream's flow, also deteriorating its quality. In fact, at certain times of the year, the entire flow may consist of waste water.

Bank Storage

Figure 3-4 shows that, as a flood wave passes a particular stream cross section, the water table may rise in the adjacent streamside deposits. The rise is caused by two phenomena. First, the stream stage, which is higher than the water table, will temporarily block ground-water runoff, thus increasing the amount of ground water in storage. Secondly, because of the increased head in the stream, water will flow from the stream channel into the ground, thus providing another component of water added to storage.

Once the flood wave begins to recede, which may occur quite rapidly, the newly added ground water will begin to flow back into the channel, rapidly at first and then more slowly as the hydraulic gradient decreases. This temporary storage of water in the near vicinity of the stream channel is called bank storage.

The rising and recession limbs of a hydrograph of a flood wave should provide clues concerning bank storage and streamside permeability. For example, where streamside deposits are of low permeability, such as clay or shale, the rising limb should be quite steep, but more gradual where the deposits are permeable. Since there would be little or no bank storage in the first case, recession curves also should

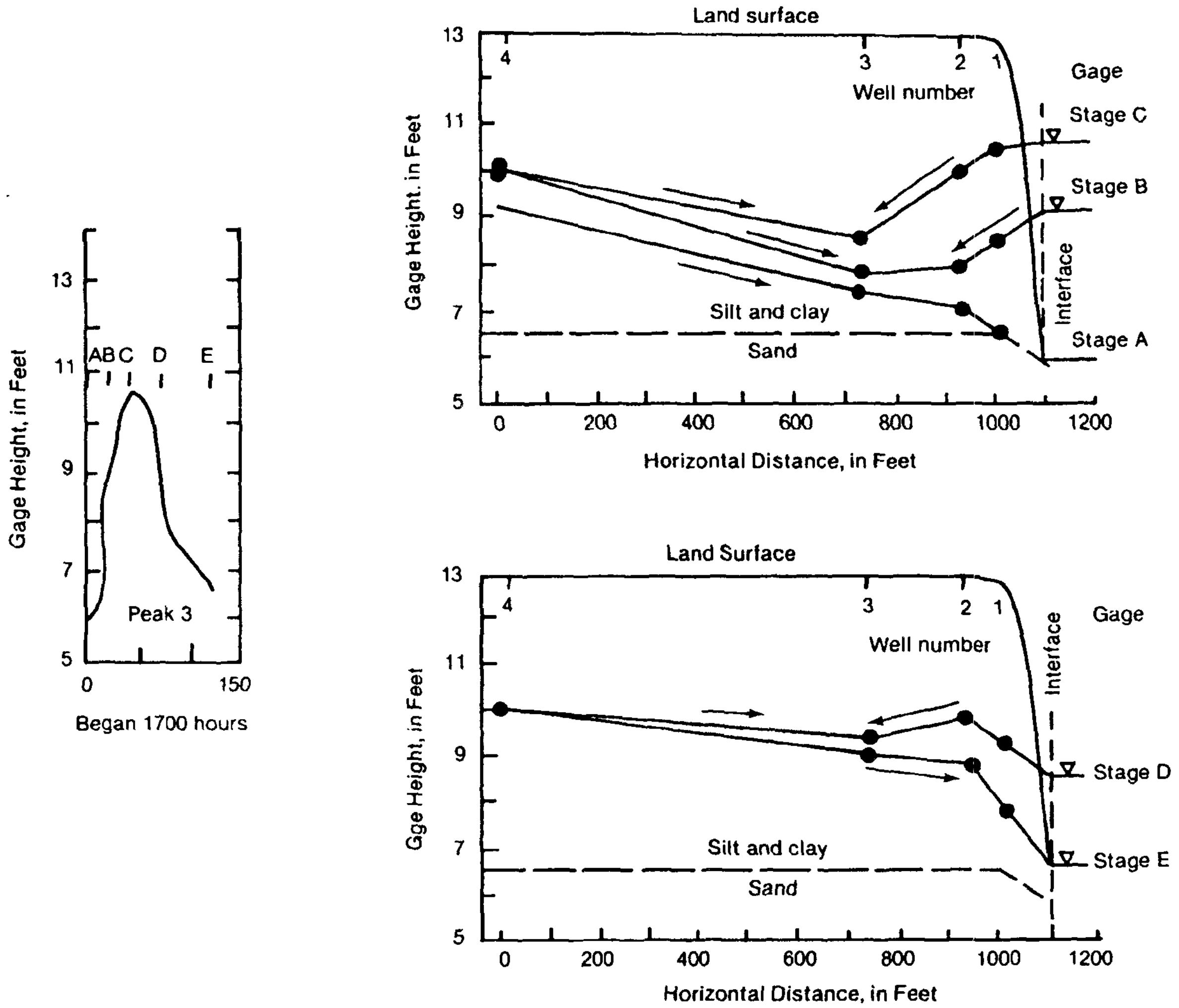


Figure 3-4. Movement of Water Into and Out of Bank Storage Along a Stream In Indiana

be steep, but the release from bank storage in a permeable basin should reduce the slope of the recession curve.

Effect of the Geologic Framework on Stream Hydrographs

Unfortunately, the discharge of ground water into a stream is not always as simple as has been implied from the above examples. As Figure 3-5 shows, an examination of the aquifer framework and its effect on a stream hydrograph is enlightening. Notice in Figure 3-5a that the stream channel is deeply cut into a shale that is overlain by sand. Ground water flows into the stream along a series of springs and seeps issuing at the sand-shale contact. During a runoff event the stream stage rises, but even at its peak, the stage remains below the top of the shale. In this case, the contribution of ground water remains constant despite the rise in stage. To separate the ground-water runoff component from the stream hydrograph, one merely needs to draw a straight line from the inflection points of the rising and falling limbs.

In Figure 3-5b the stream channel is cut into a deposit of sand that is underlain by shale. Ground water flows into the stream, but as the stage rises, ground-water runoff decreases and eventually stops. Surface water then begins to flow into the ground where it is retained as bank storage. As the stage declines, ground water again starts to discharge into the channel eventually providing the entire flow. This is the classic case of bank storage. Hydrograph separation is more difficult in this case.

Figure 3-5c is a combination of the previous two

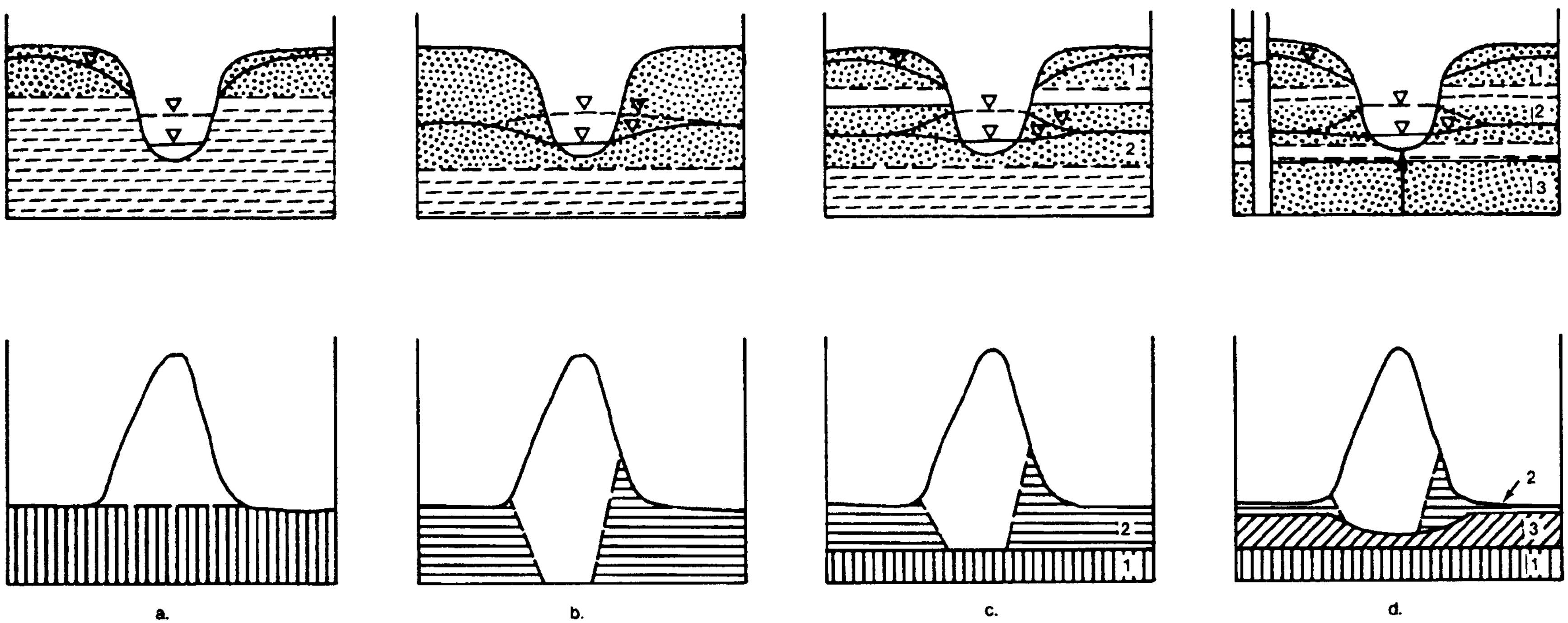


Figure 3-5. The Aquifer Framework in the Vicinity of a Stream Plays a Major Role in Ground-Water Runoff and Hydrograph Separation

examples. Ground water from a perched aquifer contributes a steady flow, while bank storage is gained and then released from the streamside aquifer. Hydrograph separation is even more difficult in this situation because of the contribution from both aquifers.

The final example, Figure 3-5d, consists of three aquifers—one perched, one in direct contact with the stream, and one deeper, confined aquifer. As the stream rises, there is a decrease in the head difference between the stream and the confined aquifer. The decrease in head difference will reduce upward leakage from the artesian aquifer, the amount depending on the thickness and vertical permeability of the confining bed and the head difference.

Single-Event Hydrograph Separation Techniques

Following a runoff event, the water held as bank storage begins to discharge into the channel. In the beginning the rate of bank storage discharge is high because of the steep water-level gradient, but as the gradient decreases so does ground-water runoff. The recession segment of the stream hydrograph gradually tapers off into what is called a depletion curve. To a large extent, the shape of the depletion curve is controlled by the permeability of the streamside deposits, although soil moisture and evapotranspiration may play important roles.

Depletion Curves

Intervals between surface runoff events are generally short and for this reason, depletion curves are plotted as a combination of several arcs of the hydrograph with the arcs overlapping in their lower parts, as shown in Figure 3-6. To plot a depletion curve, tracing paper is placed over a hydrograph of daily flows and, using the same horizontal and vertical scales, the lowest arcs of the hydrographs are traced, working backward in time from the lowest discharge to a period of surface runoff. The tracing paper is moved horizontally until the arc of another runoff event coincides in its lower part with the arc already traced; this arc is plotted on top of the first. The process is continued until all the available arcs are plotted on top of one another.

The upward curving parts of the individual arcs are disregarded because, presumably, they are affected by channel storage or surface runoff, or both. The resulting continuous arc is a mean or normal depletion curve that represents the trend that the hydrograph would have followed during a protracted dry period.

Even for the same stream, there may be appreciable differences in the shape of the depletion curve at different times of the year. This is largely due to evaporation, transpiration, and temperature effects. In cases such as these, a family of depletion curves may be constructed. One curve should represent winter when there is little or no evapotranspiration, another curve should represent the summer when evapotranspiration is at its maximum, and perhaps a third curve should be prepared to represent intermediate conditions.

Depletion curves are the basis for estimating ground-water runoff during periods of surface runoff. They also shed a great deal of light on the characteristics of a ground-water reservoir.

Hydrograph Separation

A flood hydrograph is a composite hydrograph consisting of surface runoff superimposed on ground-water runoff. When attempting to separate these two components of flow, however, some problems generally occur. Whatever method is employed, there is always some question as to the accuracy of the division. One can only say that, in any given case, ground-water runoff is probably not less than about "x" or more than about "y." Keeping in mind the complexities of a stream hydrograph brought about by variable parameters, and particularly the geology of the basin, an attempt will be made to develop some logical methods for hydrograph separation.

Using the flood hydrograph in Figure 3-7a, we can see that point A represents the start of surface runoff. Using a previously prepared depletion curve, the original recession can be extended to B. The area below AB represents the ground-water runoff that would have occurred had there been no surface runoff. Point D represents the end of surface runoff. A depletion curve can be matched with the recession limb, extending it from D to C. A partial envelope has now been formed that shows the upper and lower limits between which a line may reasonably be drawn to separate the two components of runoff. This assumption ignores possible effects brought about by difference in the geologic framework. This envelope forms a basis for the most commonly used separation methods which are described below.

Method 1. Using a depletion curve and starting at D in Figure 3-7b, extend the recession curve back to a line drawn vertically through the peak of the hydrograph (C). A second line is then extended from A, the start of surface runoff, to C. This method is more likely to be valid where ground-water runoff is relatively large and reaches the stream quickly.

Not uncommonly, the end of surface runoff is difficult to

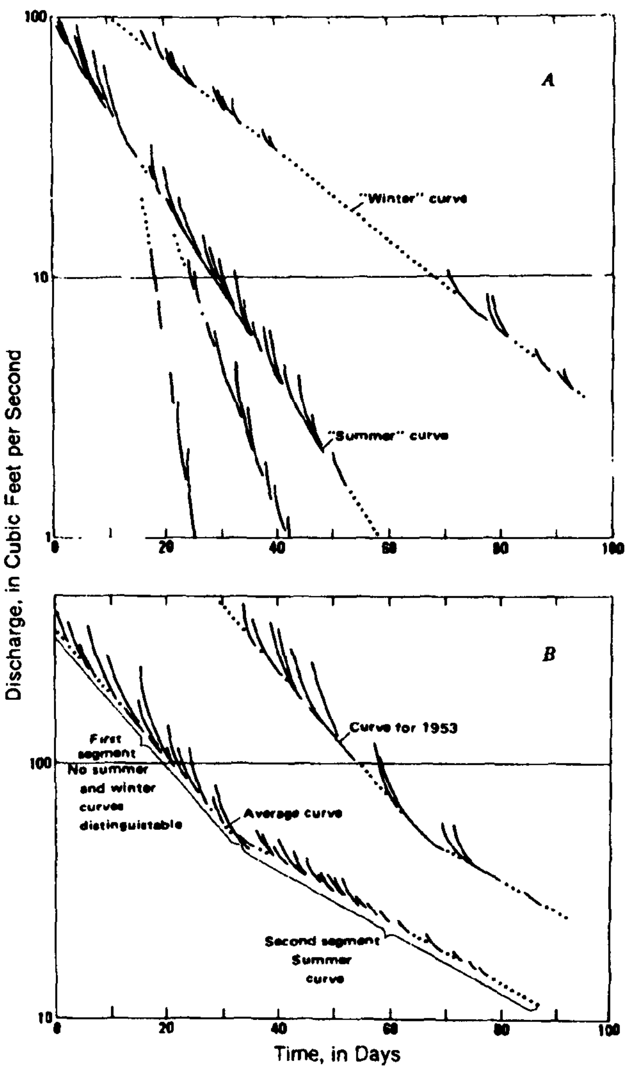


Figure 3-6 Ground-Water Depletion Curves Have Different Shapes that Reflect the Seasons

determine, but point D can be estimated by means of the equation

$$N=A^2 \quad (1)$$

where N = the number of days after a peak when surface runoff ceases and A = the basin area, in square miles. The distance N is measured directly on the hydrograph.

Method 2. In this example in Figure 3-7b, separation is accomplished merely by extending a straight line, originating at the start of surface runoff (A), to a point on the recession curve representing the end of surface runoff (D). This method of separation is certainly the simplest and is justifiable if little is known about the aquifer framework.

Method 3. In this example, also in Figure 3-7b, the prerunoff recession line is extended from A to a point directly under the hydrograph peak (B). From this point a second line is projected to D, the end of surface runoff.

The separation technique to be employed should be based on knowledge of the hydrogeology of the basin, keeping in mind the effect of the geologic framework on the hydrograph.

Separation of Complex Hydrographs

Commonly runoff events occur at closely spaced intervals and there is insufficient time for the recession curve to develop before runoff again increases. This complicates hydrograph separation.

Figure 3-7c shows two methods that can be used to determine ground-water runoff under a complex hydrograph, which represents two storms.

Method 1. The recession curve preceding the first runoff event is continued to its intersection with a line drawn through the first peak (A-B). The distance N is calculated and measured. The recession limb of the first event is continued to its intersection with the N-days line (C-D). Line B-D is then constructed. The first recession trend is continued to its intersection with a line drawn through the peak of the second runoff event (CD-E). From this point (E), the line is extended N days.

Method 2. As Figure 3-7c shows, the easiest method is to project a straight line from A to F. Although by far the simplest, this technique is not necessarily any less accurate than Method 1.

Hydrograph Separation by Chemical Techniques

Generally ground water is more highly mineralized than surface runoff. During baseflow the stream's natural quality is at or near its maximum concentration of dissolved solids, but as surface runoff reaches the channel and provides an increasing percentage of the flow, the mineral content is diluted. Following the discharge peak, surface runoff diminishes, ground-water runoff increases, and the mineral content again increases.

Several investigators have used the relation between runoff and water quality to calculate the ground-water contribution from one or more aquifers or to measure streamflow. This method of hydrograph separation, which requires the solution of a series of simultaneous equations, is based on the concentration of a selected chemical parameter that is characteristics of ground-water and surface runoff.

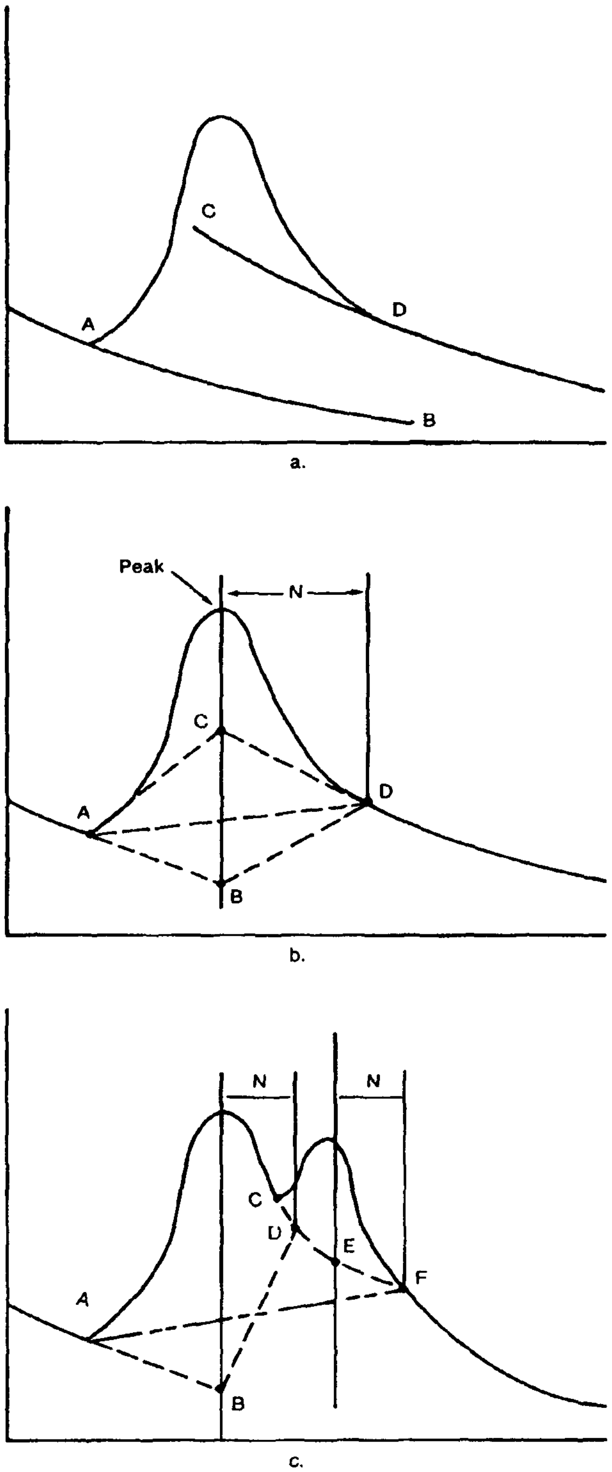


Figure 3-7. Separation of the Stream Hydrograph

The basic equations, which may take several forms, are as follows:

$$Qg + Qs = Q$$

$$CgQg + CsQs = CQ \qquad (2)$$

where Qg, Qs, and Q are ground-water runoff, surface runoff, and total runoff, respectively; and Cg, Cs, and C represent the concentration of dissolved mineral species or specific conductance of ground water, surface runoff, and total runoff, respectively. Usually specific conductance is used as the C parameter because of the relative ease of obtaining it.

If Cg, Cs, C, and Q are known we can determine the quantity of ground-water runoff as follows:

$$Qg = Q\,(C - Cs)/(Cg - Cs) \qquad (3)$$

C is determined by measuring the specific conductance in a well, in a series of wells, or during baseflow. The quality of surface runoff (Cs) is obtained from analysis of overland flow or, possibly in the case of small streams, at the period of peak discharge when the entire flow consists of surface runoff. It is assumed Cg and Cs are constant. C and Q are measured directly.

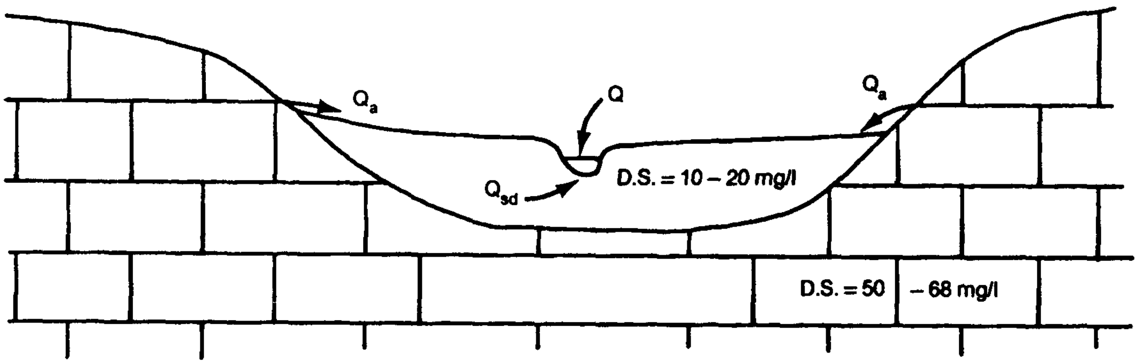
Visocky (1970) used continuous recording equipment to measure specific conductance and stage (water level) in the Panther Creek Basin in north-central Illinois. By using the equations given above, he calculated the ground-water runoff component of the stream on the basis of the relationship between discharge and specific conductance. He also calculated and compared ground-water runoff as determined from a ground-water rating curve and found that the chemical method provided a lower estimate under normal conditions than did the rating curve technique. On the other hand, the chemical method indicated more ground-water runoff following storms that were preceded by extended dry periods, which had caused considerable declines in water level in nearby observation wells.

During baseflow, the quantity of ground-water discharge from surficial sand and from limestone in the Floridan artesian aquifer into Econfina Creek in northwest Florida was distinguished by Toler (1965). In this case, as Figure 3-8 shows, the artesian water had a dissolved solids content of 50-68 mg/L, while that from the surficial sand was only 10-20 mg/L. The artesian water discharged through a series of springs along the central part of the basin and amounted to 70 to 75 percent of the stream's baseflow. The equation used for this analysis is as follows:

$$Qa = (C - Csd)/(Ca - Csd)\,Q \qquad (4)$$

where Qa = artesian runoff, Q = runoff and Csd, Ca, and C represent the dissolved solids in water from the sand, the artesian aquifer, and during any instant in the stream, respectively. Of course,

$$Q - Qa = Qsd \qquad (5)$$



$$Q_a + Q_{sd} = Q \qquad Q_a = ? \quad C_a = 50$$
$$CQ_a + CQ_{sd} = CQ \qquad Q_{sd} = ? \quad C_{sd} = 10$$
$$Q = 18 \quad C = 43$$

$$Q_a + Q_{sd} = 18 \qquad -10Q_a - 10Q_{sd} = -180$$
$$50\,Q_a + 10\,Q_{sd} = 43 \times 18 \qquad 50Q_a + 10Q_{sd} = 774$$
$$40Q_a = 594$$
$$Q_a = 14.85 \text{ fs}$$

$$Q_a = \frac{Q\,(C - C_{sd})}{C_a - C_{sd}} \quad \text{OR} \quad Q_a = \frac{18(43 - 10)}{50 - 10} = \frac{594}{40} = 14.85 \text{ cfs}$$

Figure 3-8. Contribution to Econfina Creek During a Period of Dry Weather Flow When the Stream Discharge Was 18 cfs and the Dissolved Solids Concentration Was 43 mg/L: From Sand Aquifer = 3.15 cfs, From Limestone Aquifer = 14.85 cfs

Continuous streamflow and conductivity measurements were collected at a gaging station on Four Mile Creek in east-central Iowa by Kunkle (1965). The basin above the gage, which contains 19.5 m^2, consists largely of till that is capped on the uplands by loess. As Figure 3-9 shows, the stream lies in a valley that contains as much as 30 feet of permeable alluvium. Ground water from the alluvium and loess, as well as the stream during low flow, has an average specific conductance of 520 micromhos (Cg) while surface runoff is about 160 micromhos (Cs).

Figure 3-10 shows continuous record of discharge and conductivity representing a storm in September 1963. Instantaneous ground-water runoff during this event was calculated for several points under the hydrograph by using the following formulas

$$Qg + Qs = Q$$
$$CgQg + CsQs = CQ \quad (6)$$

where Qg = ground-water runoff, Qs = surface runoff, Q = runoff, and Cg, Cs, and C = specific conductance of ground-water runoff, surface runoff, and runoff, respectively. As determined from the graphs in Figure 3-10, where Q = 2.3 cfs, C = 410; Cg = 520 and Cs = 160, then Qg is 1.6 cfs. Therefore, when the stream's discharge (Q) was 2.3 cfs, ground-water runoff was 1.6 cfs. This calculation provides one point under the hydrograph. Several other points need to be determined so that a separation line can be drawn.

Computer Separation Programs

Various methods of hydrograph separation have been described, all of which are laborious, time consuming, and, commonly, open to questions of accuracy and interpretation. In each case a mechanical technique is used to provide a number of points on a hydrograph through which a line can be drawn that separates ground-water runoff from surface runoff. Once this line is determined, one must measure, directly on the hydrograph, the daily components of streamflow and then sum the results.

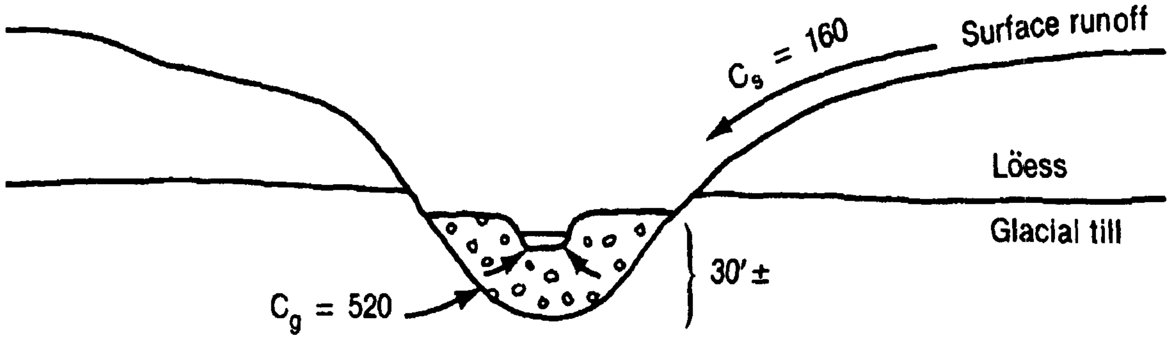


Figure 3-9. Four Mile Creek, Iowa

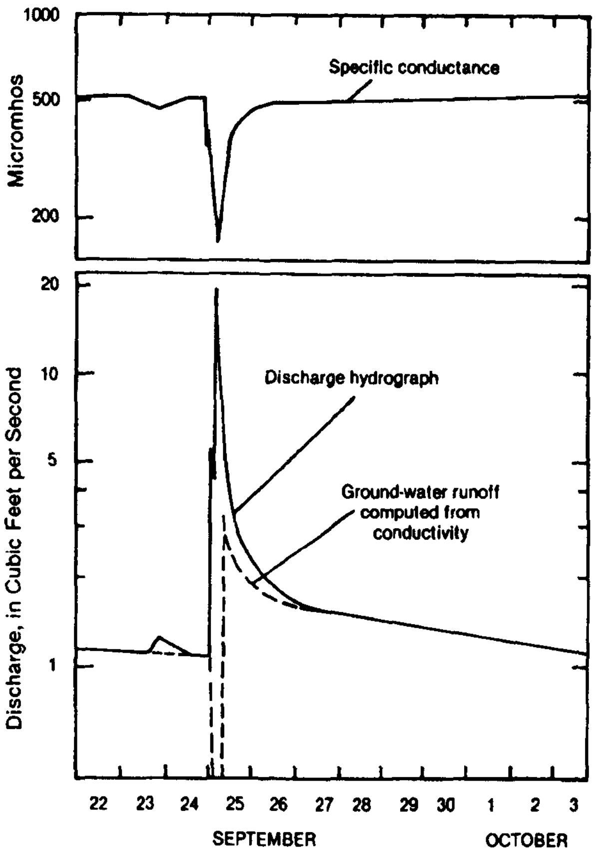


Figure 3-10. Hydrographs Showing Water Discharge, Specific Conductance, and Computed Ground-Water Runoff in Four Mile Creek near Traer, Iowa, September and October 1963

Annual ground-water runoff divided by total discharge provides the percentage of streamflow that consists of ground water. Effective ground-water recharge is that quantity of precipitation that infiltrates, is not removed by evapotranspiration, and eventually discharges into a stream.

Effective ground-water recharge rates can be easily estimated with a computer program described by Pettyjohn and Henning (1979). This program separates the hydrograph by three different methods, provides monthly recharge rates and an annual rate, produces a flow-duration table, and gives the operator the option of generating the separated hydrograph and a flow-duration curve with a line printer; as illustrated in Figure 3-11. The data base is obtained from annual streamflow records, which are published by the U.S. Geological Survey. The computer program will operate on a mainframe or microcomputer.

Ground-Water Rating Curve

A widely used technique to measure streamflow is the surface-water rating curve, which shows the relation between stage and discharge. Figure 3-12 shows a similar curve, called a ground-water rating curve, that illustrates the relation between the water table and streamflow. Prepared for those aquifer-stream systems that are hydrologically connected, the ground-water rating curve can be used to separate ground-water runoff from a stream hydrograph.

To prepare the curve, synchronous water table and stream discharge measurements are required. Ground-water levels are obtained either from: (1) a series of wells spread throughout the basin, (2) a series of wells, each of which represents an area of similar geology, or (3) a single near-stream well. Wells influenced by pumping should not be used. If more than one well is used, water levels, referred to some datum, such as sea level, must be averaged to form a composite curve. Furthermore, measurements of both ground water and stream stage should be made only during rainless

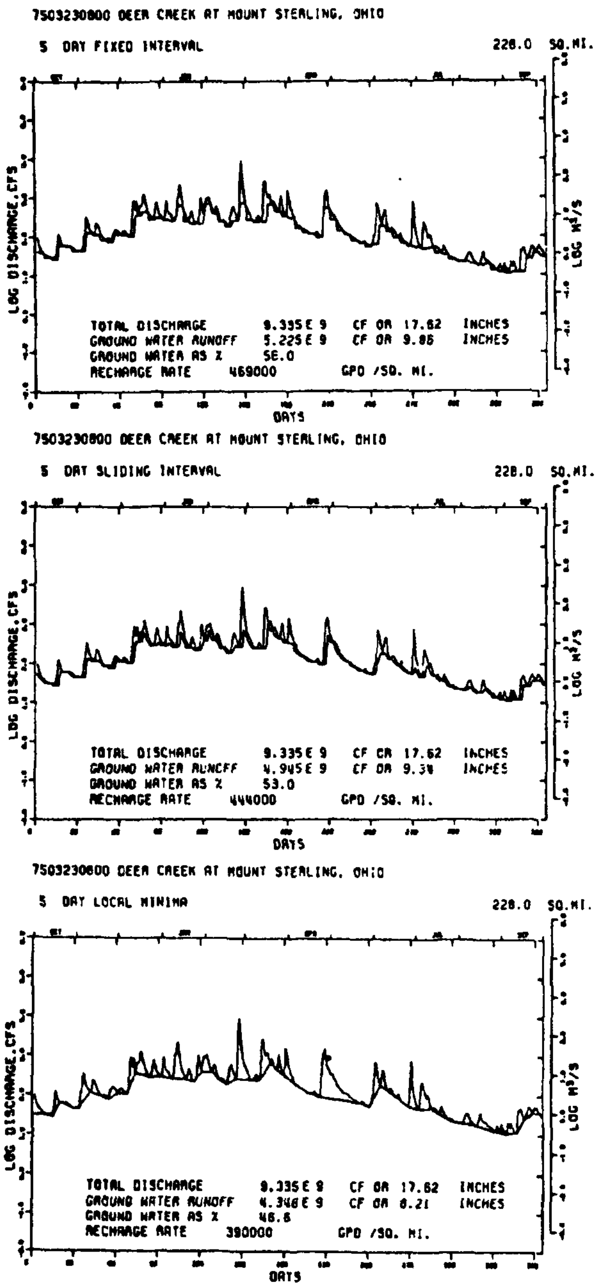


Figure 3-11. Deer Creek Hydrographs Separated by Three Methods and Statistical Data

intervals when streamflow consists entirely of ground-water runoff. Selected water-level measurements are plotted on a graph with the mean daily streamflow and a smooth curve is drawn through the points.

The graph is used by determining, either from individual measurements or water-level recorder data, the ground-water stage, reading across the graph to the curve, and then reading down to the stream discharge. For example, in Figure 3-12 when the mean ground-water stage is 44.5 feet, ground-water runoff is 10 cfs. Any flow in excess of this amount is surface runoff. Daily values of ground-water runoff are plotted on the stream hydrograph, eventually forming a continuous line throughout the period of record.

Although wells produce only limited yields from crystalline rocks in the Piedmont Upland part of the Delaware River Basin, streams have unusually high base flows. Olmsted and Hely (1962) used a ground-water rating curve to study this apparent inconsistency in a 287 m^2 part of the Brandywine Creek basin in southeastern Pennsylvania, as illustrated in Figure 3-13.

Bedrock units in the dissected upland basin, which consists largely of folded Precambrian and Paleozoic igneous and metamorphic rocks, have similar hydrologic characteristics. Weathered material of variable thickness mantles the area and the water table lies largely within this zone. Precipitation averages about 44 inches.

The 16 observation wells used in this study ranged from 12 to 40 feet in depth; all tapped a weathered schist aquifer. Six or seven wells were measured weekly or immediately after storms and wells De-3, Ch-13, and Ch-14 were selected as index wells. The average depth to water in all of the wells was 17.45 feet and the annual fluctuation was 5.75 feet.

Figure 3-14 shows a composite hydrograph of the three index wells and the discharge of Brandywine Creek. The curves have similar trends, differing only in amplitude following runoff events. This is to be expected because of the quick response time of a stream. Certainly the closer an observation well is to a stream, the more nearly the hydrographs will approach a similar shape.

The rating curve in Figure 3-15 shows the relation between ground-water runoff and ground-water stage in the Brandywine Creek basin. Notice the elliptical pattern of the data, which approach a straight line from October through March but then loop back during spring, summer, and early fall. Although confusing at first glance, the significance of the loop becomes readily apparent when the changes that occur in a ground-water reservoir throughout a 12-month period in a humid area are considered. From late fall to spring, the ground-water stage rises because there are little or no losses to evapotranspiration, soil moisture may be at or above field capacity, and ground-water recharge occurs. The water table reaches its peak during the spring runoff. From April to October, however, large quantities of ground water are removed by evapotranspiration, the soil moisture becomes so depleted there is little or no recharge, and the quantity of water in storage decreases because ground-water runoff exceeds recharge. Thus,

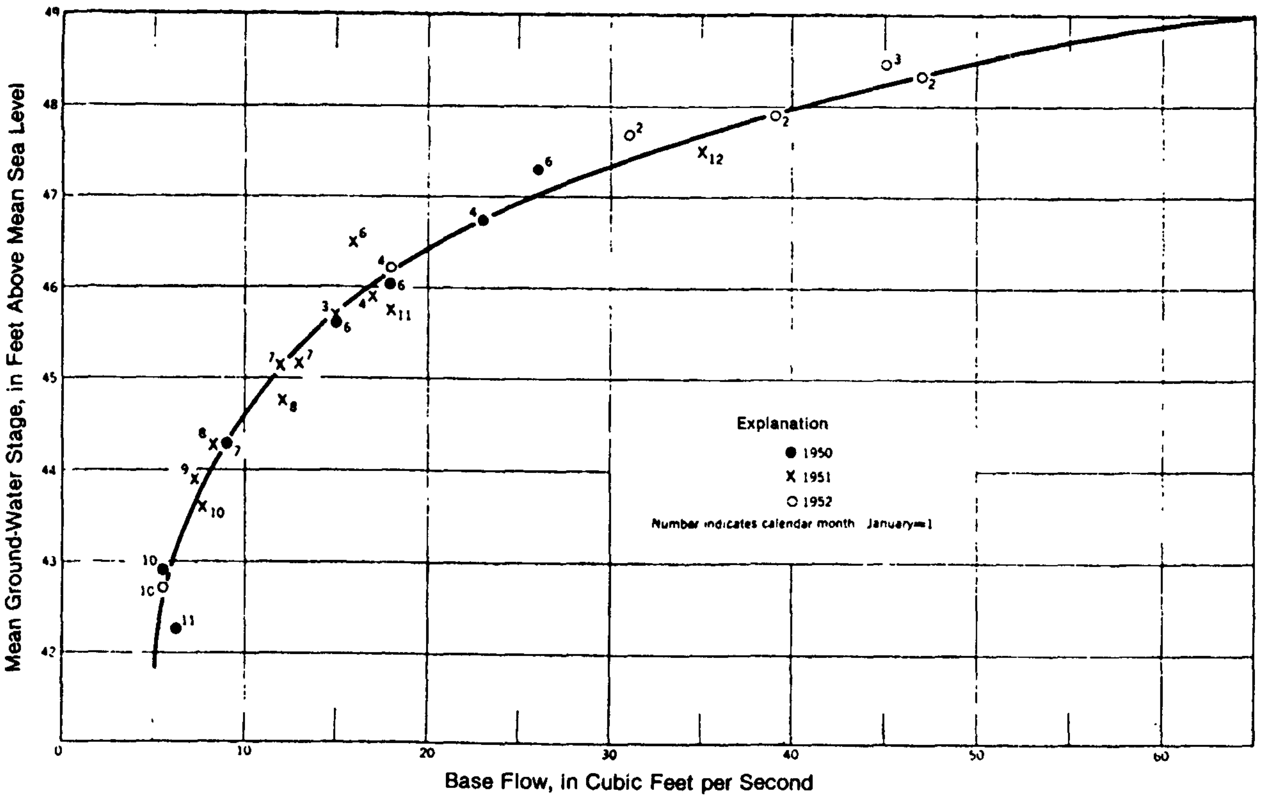


Figure 3-12. Rating Curve of Mean Ground-Water Stage Compared with Base Flow of Beaverdam Creek, Maryland

the elliptical shape of the data on the rating curve is controlled by evapotranspiration.

Using the rating curve, Olmsted and Hely (1962) separated the Brandywine Creek hydrograph, shown in Figure 3-16, and found that over a six year period, ground-water runoff accounted for 67 percent of the total flow. This compares favorably with the 64 percent determined for North Branch Rancocas Creek in the coastal plain of New Jersey; 74 percent for Beaverdam Creek in the coastal plain of Maryland (Rasmussen and Andreason, 1959); 42 percent for Perkiomen Creek, a flashy stream in the Triassic Lowland of Pennsylvania; and 44 percent for the Pomperaug River Basin, a small stream in Connecticut (Meinzer and Stearns, 1928).

During certain times of the year, when the water table lies at a shallow depth and large quantities of water are lost by evapotranspiration, a single rating curve cannot be used to separate a hydrograph with any degree of accuracy. As Figure 3-17 shows, Schicht and Walton (1961), in their study of Panther Creek basin in Illinois, developed two rating curves. One is used when evapotranspiration is very high and the other when evapotranspiration is small. Double rating curves also can be used to estimate evapotranspiration losses.

Evapotranspiration can also be calculated from the graph used by Olmsted and Hely (1962) in the case cited above. For example, when the ground-water stage was 80 inches, streamflow was expected to be about 550 cfs in February and March but only 400 cfs in June. In this case, the difference, about 150 cfs, is due to evapotranspiration.

Seepage or Dry Weather Measurements

Seepage or dry-weather measurements consist of flow determinations made at several locations along a stream during a short time interval. It is essential that there be no surface runoff during these measurements. Many investigators prefer to conduct seepage runs during the stream's 90 percent flow, that is, when the flow is so low that it is equaled or exceeded 90 percent of the time.

It is often implied that the 90 percent flow is the only time the flow consists entirely of ground-water runoff. This is not necessarily the case. The 90 percent flow-duration period, depending on geographic location and climate, commonly occurs during the late summer and fall when

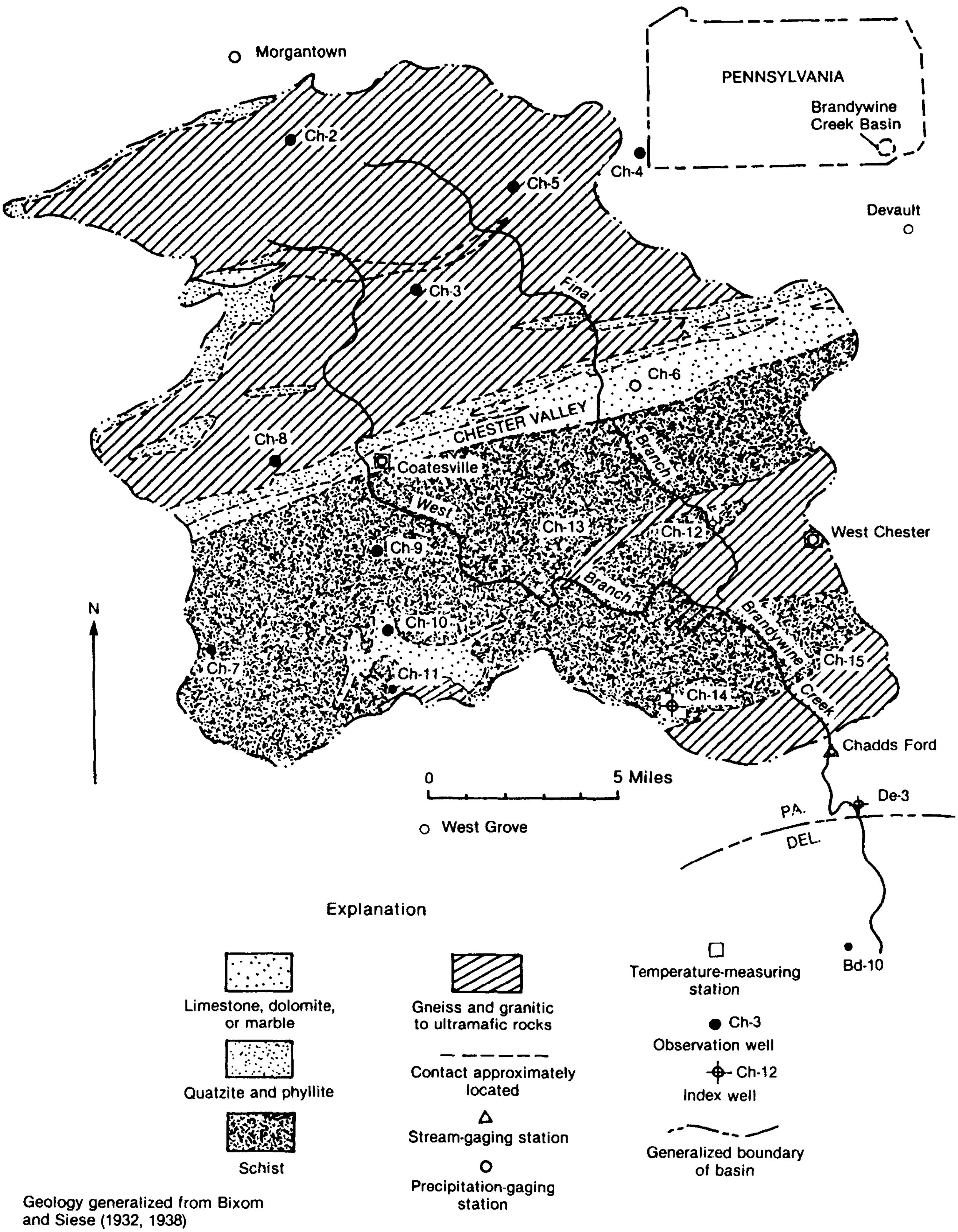


Figure 3-13. Sketch Map of Brandywine Creek Basin, Showing Generalized Geology and Location of Hydrologic and Meteorologic Stations Used in Report

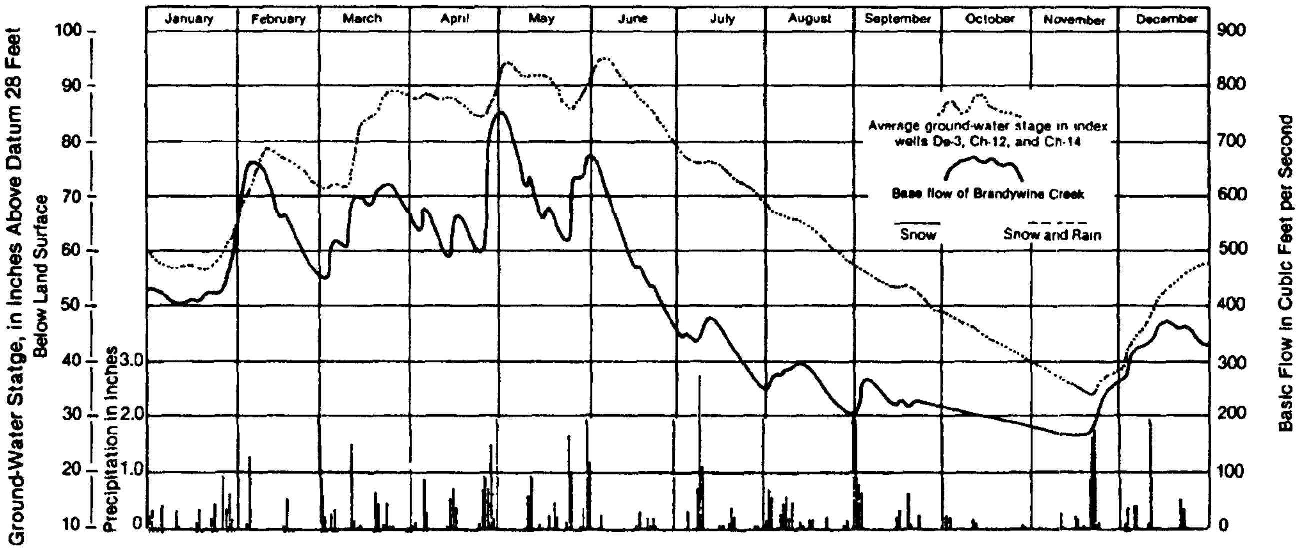


Figure 3-14. Composite Hydrograph of Three Index Wells and the Discharge of Brandywine Creek

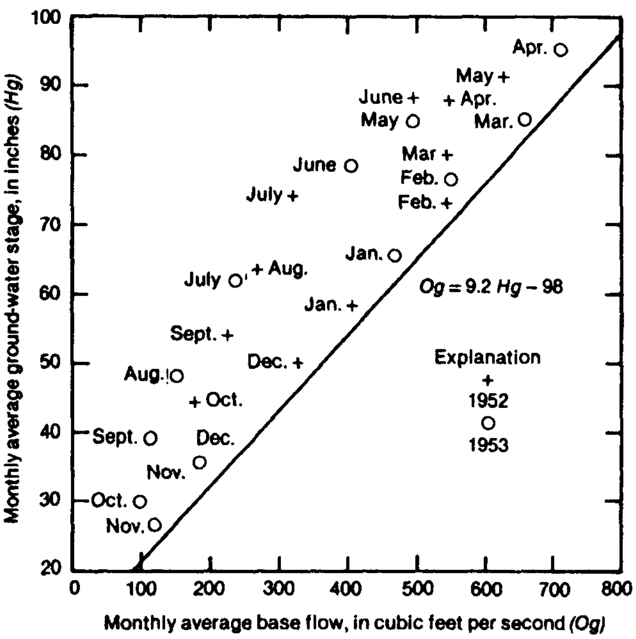


Figure 3-15. Relation of Monthly Average Base Flow to Ground-Water Stage in the Brandywine Creek Basin

soil moisture is depleted, there is little or no ground-water recharge, and the water table, having declined to its lowest level, has a low gradient. Under these conditions, ground-water runoff is minimal. However the physical aspect of the system may change following a recharge period and ground-water runoff may account for a substantial portion of the stream's flow. Hydrograph analyses, using techniques already described, may readily show that ground water provides 50 to 70 percent or more of the runoff. Therefore, the 90 percent flow may reflect only a small fraction of the total quantity of ground-water runoff.

Seepage measurements permit an evaluation of ground-water runoff (how much there is and where it originates) and provides clues to the geology of the basin as well. The flow of some streams increases substantially in a short distance. Under natural conditions this increase probably indicates deposits or zones of high permeability in or adjacent to the stream channel. These zones may consist of deposits of sand and gravel, fracture zones, solution openings in limestone or merely by local facies changes that increase permeability. In gaining stretches, ground water may discharge through a number of springs and seeps, along valley walls or the stream channel, or seep upward directly into the stream. Areas of significant ground-water discharge may cause the formation of quicksand.

In areas where the geology and ground-water systems are not well known, streamflow data can provide a means of testing estimates of the ground-water system. If the streamflow data do not conform to the estimates, then the geology must be more closely examined. For example, the northwest corner of Ohio is crossed by the Wabash and Fort Wayne moraines between which lies the St. Joseph River. As indicated by the Glacial Map of Ohio (Goldthwait and others, 1961), the St. Joseph basin consists mainly of till. However, low-flow measurements show that the discharge of the river increases more than 14 cfs along its reach in Ohio,

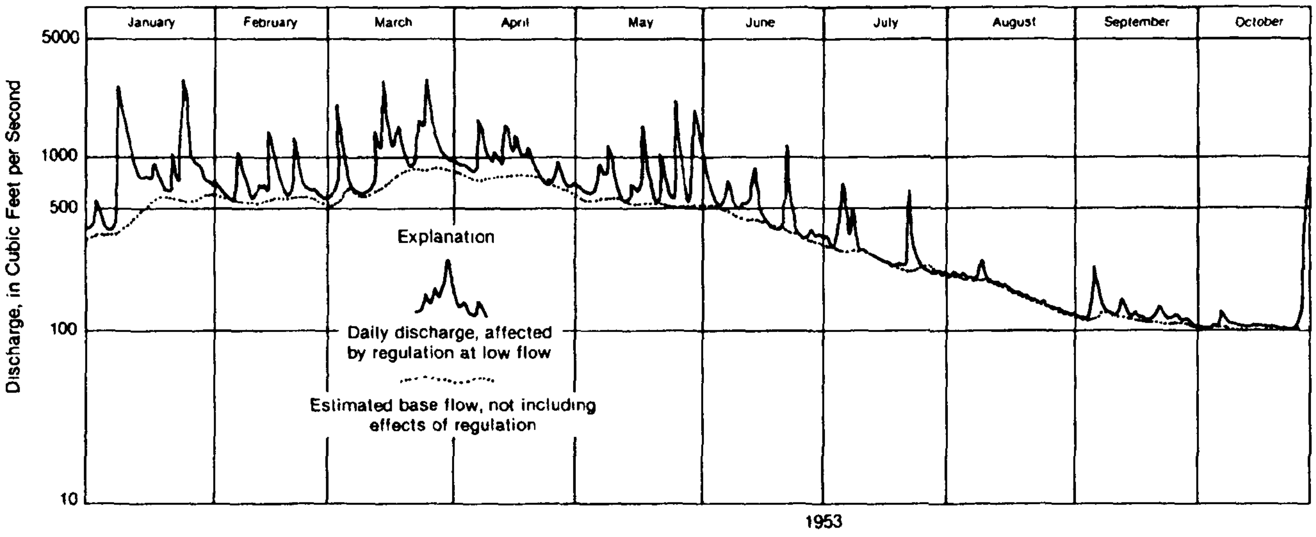


Figure 3-16. Hydrograph of Brandywine Creek at Chadds Ford, Pennsylvania, 1952-53

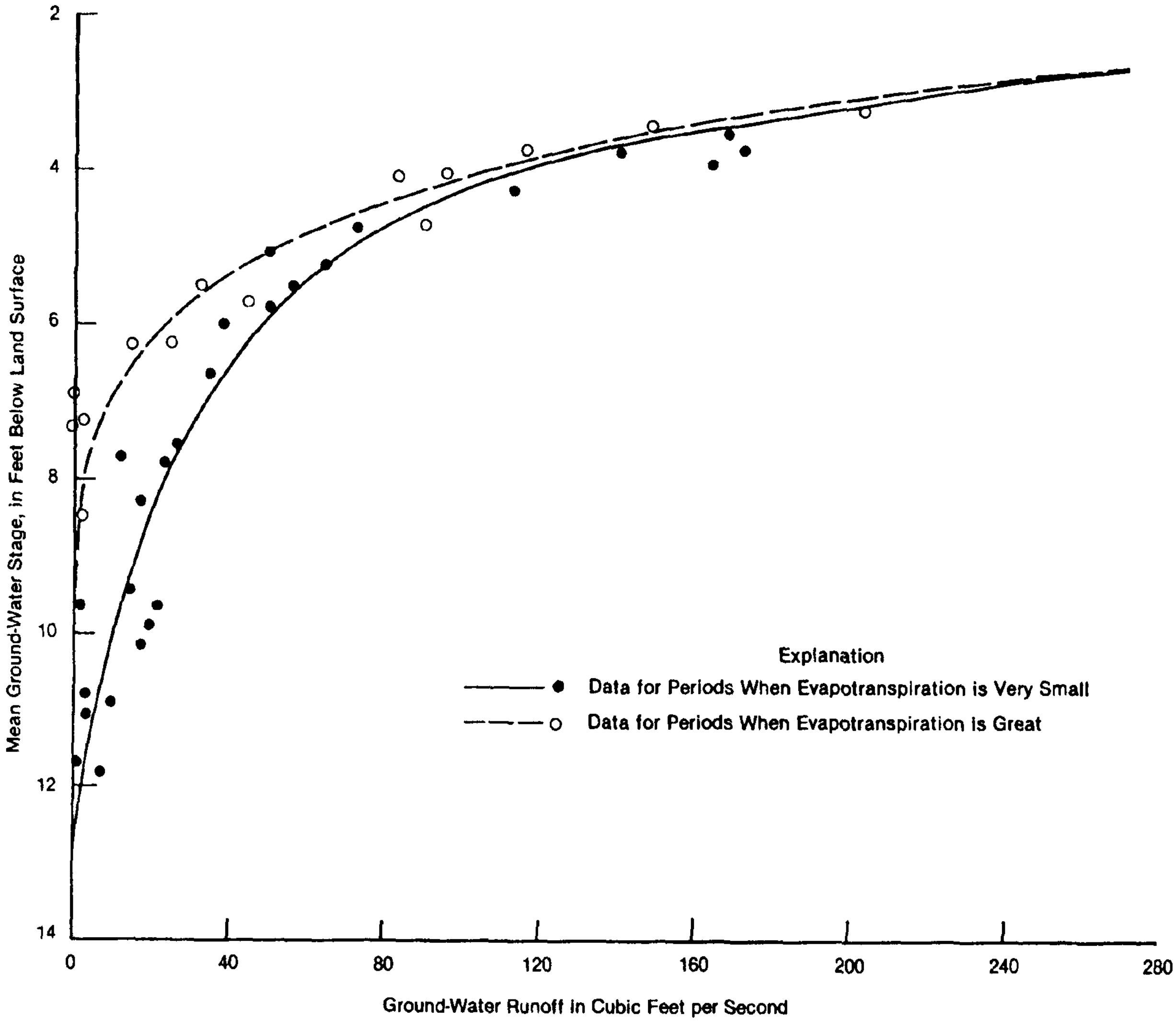


Figure 3-17. Rating Curves of Mean Ground-Water Stage vs. Ground-Water Runoff at Gaging Station 1, Panther Creek Basin, Illinois

indicating that the basin contains a considerable amount of outwash. Thus, hydrologic studies indicate the need for geologic map modification.

On the other hand, geologic maps may indicate reasonable locations for constructing stream gaging stations for hydrologic monitoring networks. The Auglaize River in northwestern Ohio rises from a mass of outwash that lies along the front of the Wabash moraine. The southwest-flowing river breaches the moraine near Wapakoneta and then flows generally north to its confluence with the Maumee River at Defiance. A gaging station is near Ft. Jennings in a till plain area and slightly above a reservoir on the Auglaize. In reality this gage measures, at a single point, the flow resulting as an end product of all causative hydrologic factors upbasin (ground-water runoff, surface runoff, slope, precipitation, use patterns, etc.)—it shows merely inflow into the reservoir. Low-flow measurements, however, indicate that nearly all of the baseflow is derived from outwash along the distal side of the Wabash moraine; there is no grain across the wide till plain downstream. It would seem that the most logical stream gage site for hydrologic evaluations would be at the breach in the Wabash moraine just downstream from the till-outwash contact.

Figure 3-18 shows a number of discharge measurements made in the Scioto River basin, which lies in a glaciated part of central Ohio. The flow measurements themselves are important in that they show the actual discharge, in this case at about 90 percent flow. In this case the discharge is reported as millions of gallons per day, instead of the usual cubic feet per second. The discharge at succeeding downstream sites on the Scioto River are greater than the flow immediately upstream. This shows that the river is gaining and that water is being added to it by ground-water runoff from the adjacent outwash deposits.

A particularly useful method for evaluating streamflow consists of relating the discharge to the size of the drainage basin (cfs/mi^2 or mgd/mi^2 of drainage basin). As Figure 3-18 shows, this technique can be used to relate the flow index (cfs/mi^2 or mgd/mi^2.) to the geology and hydrology of the area. A cursory examination of the data shows that the flow indices can be conveniently separated into three distinctive units. These units are arbitrarily called Unit I (0.01 to 0.020 mgd/mi^2), Unit 2 (0.021 to 0.035 mgd/mi^2) and Unit 3 (0.036 to 0.05 mgd/mi^2). The Olentangy River and Alum and Big Walnut Creeks fall into Unit I, Big Darby and Deer Creeks into Unit 2, and the Scioto River, Walnut Creek, and the lower part of Big Walnut Creek into Unit 3. Notice that even though the latter watercourses fall into Unit 3, the actual discharge ranges widely—from 3.07 to 181 mgd.

Logs of wells drilled along the streams of Unit I show a preponderance of fine-grained material that contains only a few layers of sand and gravel, and wells generally yield less than 3 gpm. Along Big Darby and Deer Creek, however, logs of wells and test holes indicate that several feet of sand and gravel underlie fine-grained alluvial material, the latter of which ranges in thickness from 5 to about 25 feet. Adequately designed and constructed wells that tap these outwash deposits can produce as much as 500 gpm. Glacial outwash, much of it coarse grained, forms an extensive deposit through which the streams and river of Unit 3 flow. The outwash extends from the surface to depths that exceed 200 feet. Industrial wells constructed in these deposits, most of which rely on induced infiltration, can produce more than 1,000 gpm. Formed by combining the seepage data and well yields with a map showing the areal extent of the deposits that are characteristic of each stream valley, the map in Figure 3-18 indicates potential well yields in the area. The potential ground-water yield map relies heavily on streamflow measurement, but nonetheless, provides, with some geologic data, a good first-cut approximation of ground-water availability.

Stream reaches characterized by significant increases in flow due to ground-water runoff, may also have unusual quality characteristics. In northern Ohio the discharge of a small stream, shown in Figure 3-19, that drains into Lake Erie increases over a 3-mile stretch from about 1 to more than 28 cfs and remains relatively constant thereafter. The increase begins at an area of springs where limestone, which has an abundance of solution openings, approaches land surface and actually crops out in the stream bottom. The till-limestone contact declines downstream eventually exceeding 90 feet in depth.

In the upper reaches of a stream, baseflow is provided by ground water that discharges from the adjacent till. Since this water has been in the ground but a short time, the mineral content is low. Electrical conductivity is probably in the range of 640 µmhos. Where streamflow begins to increase significantly, the limestone aquifer provides the largest increment. Furthermore, the bedrock water contains excessive concentrations of dissolved solids (electrical conductivity of about 2,400 µmhos), hardness, and sulfate, and in this stretch calcite precipitates on rocks in the stream channel. The fish population in the upper reaches is quite abundant until the stream reaches the limestone discharge zone. At this point, the population quickly diminishes and remains

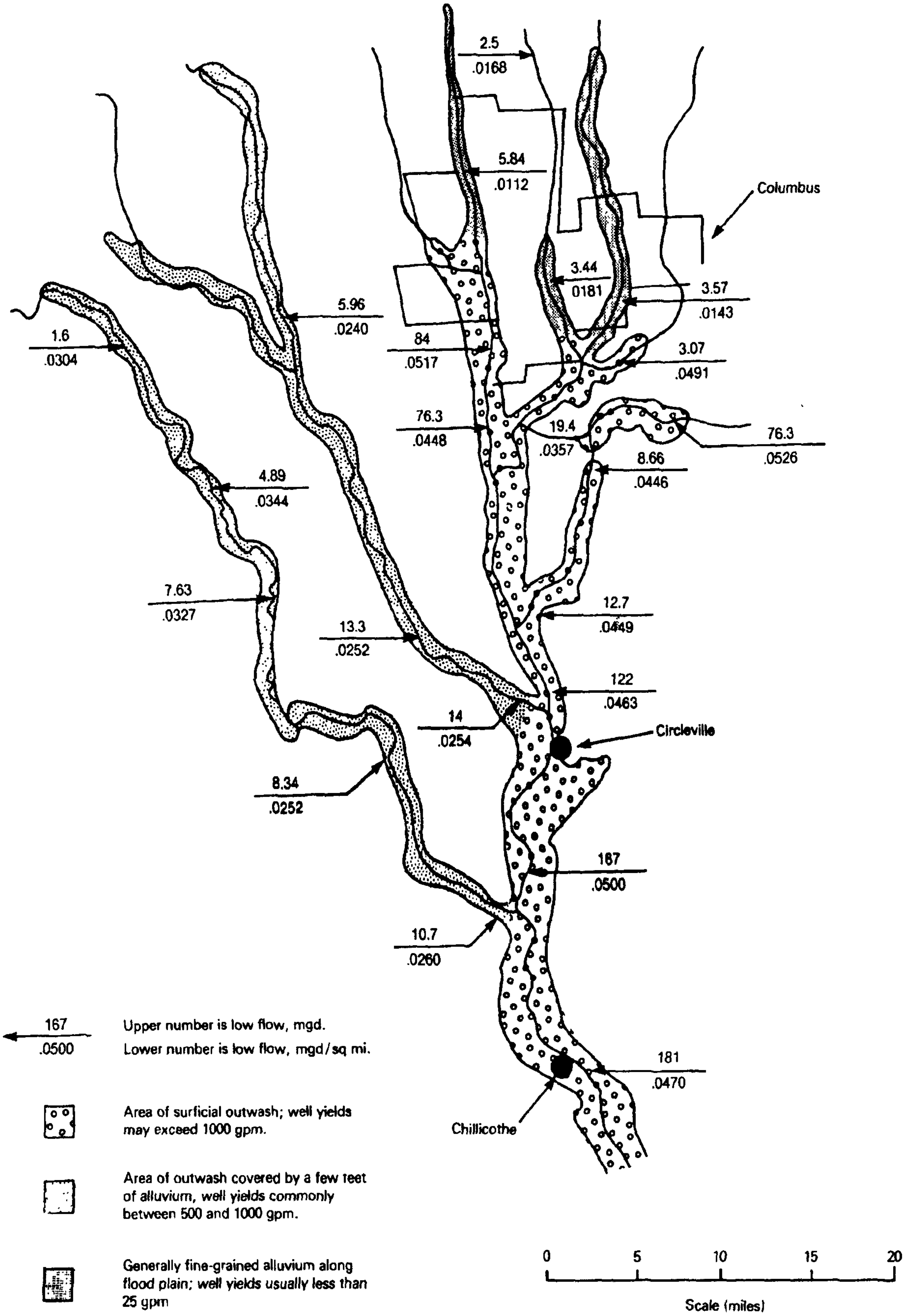


Figure 3-18. Discharge Measurements in the Scioto River Basin, Ohio

Station Number	1	2	3	4	5	6	7
No. species	10	13	10	14	13	13	2
No. indiv.	980	1527	256	520	184	71	2
D.O.	10.8	9	9.5	11.3	9.6	9.0	8.7
Q	0	0	11.76	17.59	22.28	24.211	27.62
Temp C	21	20.5	13	16.5	16	17.0	17
pH	8.27	8.17	7.76	7.98	8.07	8.13	8.12
Alk	285	253	277	250	253	255	
CO_2	4	1.0	14	6	3	2	
Cond.	638	583	2410	2340	2370	2380	2340

pH ↑ as CO_2 ↑ & $CaCO_3$ ↓ (travertine)

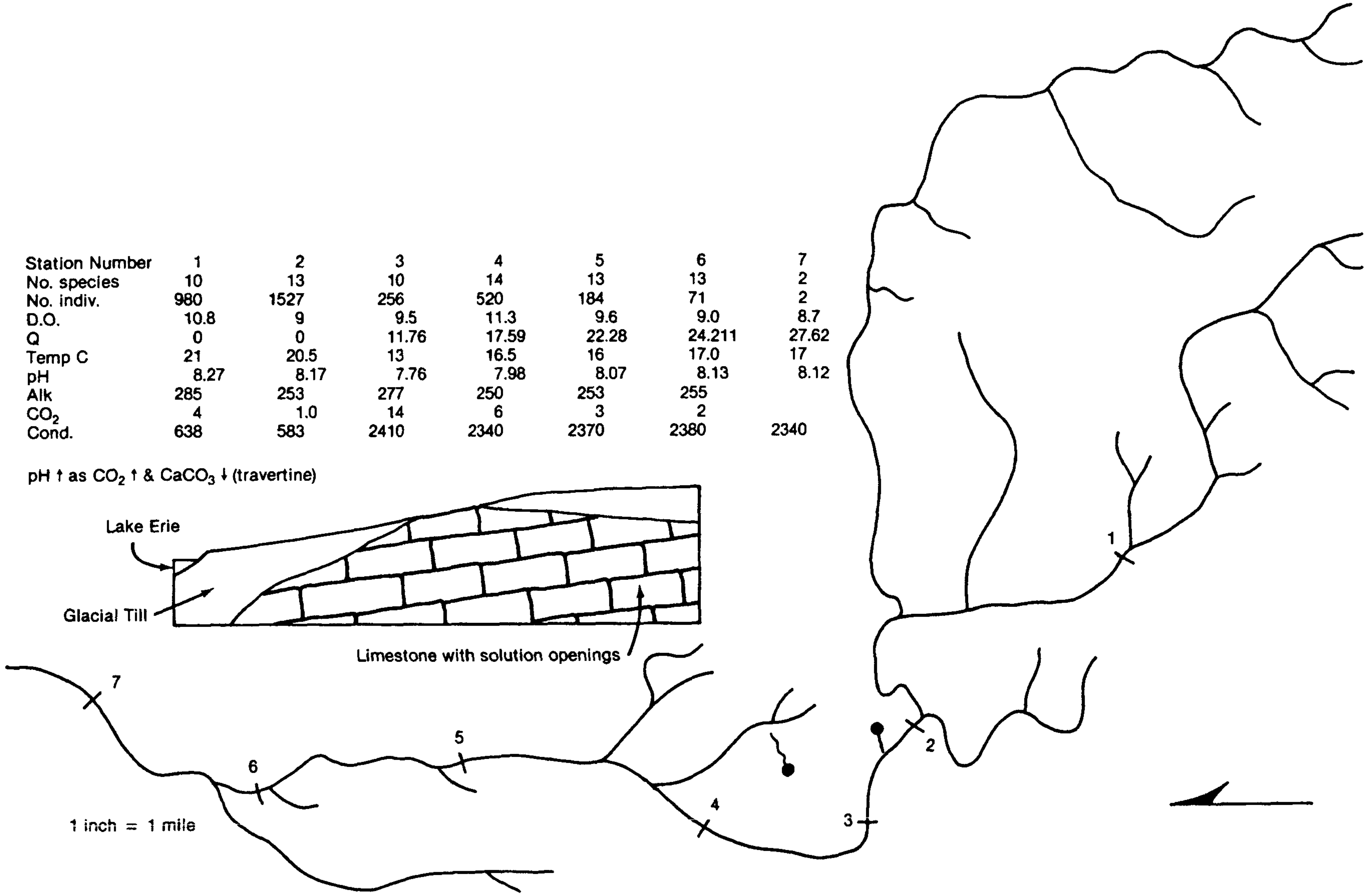


Figure 3-19. Green Creek Drainage Basin (Seneca and Sandusky Countys, Ohio)

in a reduced state throughout the remaining length of the stream. No doubt the reduction in fish population is related to the quality of the water.

In describing the hydrology of Wolf Creek in east-central Iowa, Kunkle (1965) used seepage measurements and water-quality data to determine the amount of ground-water runoff provided by alluvium and limestone. As Figure 3-20 shows, the 325 mi^2 basin is mantled by till and underlain by limestone and shale, but the valley itself contains about 40 feet of permeable alluvium. Well data show that the stream is hydraulically connected with the limestone aquifer along a 5-mile stretch and baseflow is provided by discharge from both the limestone and the alluvium. On either side of this reach the limestone potentiometric surface is below the stream bed.

Measurements were made at three stations during low-flow conditions. The discharge 8 miles upstream from the limestone discharge area was 16.4 cfs, midway along the reach was 29.8 cfs, and 7 miles downstream was 37.0 cfs. Water from the limestone has an average conductivity of 1,330 µmhos, while that from the alluvium and upstream-derived baseflow average 475 µmhos. After mixing, the surface water had a conductivity of 550 µmhos.

Using a slight modification of the equations given previously, it is possible to calculate the amount of ground-water runoff from the limestone in this reach under the given conditions.

$$Ci\,Qi + CaQa + CbQb = CQo \quad (7)$$

$$Qi + Qa + Qb = QO$$

where Qi, Qa, Qb, QO are the discharge from upstream (inflow), from the alluvium, from the limestone, and from the outflow respectively, and Ci, Ca, Cb and C represent the conductivity of the inflow from upstream, from the alluvium, from the limestone, and from the outflow water. Substituting:

$$475\ Qi + 475\ Qa + 1{,}330\ Qb = 20{,}350$$
$$-475Qi - 475\ Qa — 475\ Qb = -17{,}575$$

$$855\ Qb = 2{,}775 \quad \text{and} \quad Qb = 3\text{-}2\ \text{cfs} \quad (8)$$

Thus in this particular stretch, the limestone was providing about 3.2 cfs of the stream's total flow of 37 cfs.

Carrying the analyses a bit further, we could assume that since the limestone provides 3 to 4 cfs during baseflow, wells tapping the limestone in this stretch could provide a like amount without dewatering the system. Since 1 cfs = 450 gpm, wells could produce a total yield of 1,350 to 1,800 gpm. Using a similar approach we could predict the minimum yield of wells

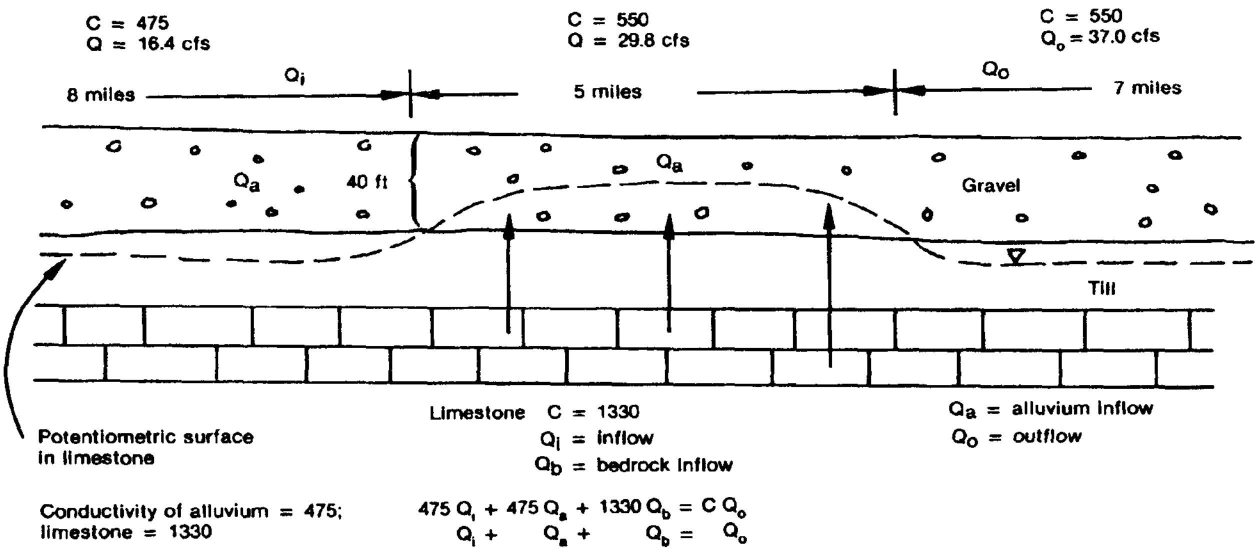


Figure 3-20. Generalized Hydrogeology of Wolf Creek, Iowa

tapping the alluvium, assuming that they would capture only the ground-water runoff.

Temperature Surveys

The temperature of shallow ground water is nearly uniform, reflecting the mean annual daily air temperature of the region. The temperature of shallow ground water ranges from a low of about 37 degrees in the north-central part of the U.S. to more than 77 degrees in southern Florida. Of course, at any particular site the temperature of ground water remains nearly constant. Surface-water temperatures, however, range within wide extremes—freezing in the winter in northern regions and exceeding 100 degrees during hot summer days in the south. Mean monthly stream temperatures during July and August range from a low of 55 in the northwest to more then 85 degrees in the southeast.

During the summer where ground water provides a significant increment of flow, the temperature of a stream in a gaining reach will decline. Conversely, during winter the ground water will be warmer than that on the surface and although ice will normally form, parts of a stream may remain open because of the inflow of the warmer ground water. In central Iowa, for example, winter temperatures commonly drop below zero and ice quickly forms on streams, ponds, and lakes. The ground-water temperature in this region, however, is about 52 degrees and, if a sufficient amount is discharging into a surface-water body, the temperature may remain above 32 degrees and the water will not freeze. In the summer, the relatively cold ground water (52 degrees) mixes with the warm surface water (more than 79 degrees) producing a mixture of water colder than that in non-gaining reaches.

Examination of winter aerial photography may show places where ice is either absent or thin. In the summer it is possible to float down a river, periodically measuring the temperature. Ground-water discharge areas are detected by temperature decrease. A third method of detection is by means of an aircraft-mounted thermal scanner. This sophisticated instrument is able to detect slight differences in temperature and would probably be more accurate than thermometry or low altitude aerial photography.

Flow-Duration Curves

A flow-duration curve shows the frequency of occurrence of various rates of flow. It is a cumulative frequency curve prepared by arranging all discharges of record in order of magnitude and subdividing them according to the percentages of time during which specific flows are equaled or exceeded; all chronologic order or sequence is lost (Cross and Hedges, 1959). Flow-duration curves may be plotted on either probability or semilog paper. In either case, the shape of the curve is an index of natural storage in a basin, including ground water. Since dry-weather flow consists entirely of ground-water runoff, the lower end of the curve indicates the general characteristics of shallow aquifers.

Figure 3-21 shows several flow-duration curves for Ohio streams. During low-flow conditions, the curves for several of the streams, such as the Mad, Hocking, and Scioto Rivers, and Little Beaver Creek, trend toward the horizontal, while Grand River, and Whiteoak and Home Creeks all remain very steep.

Mad River flows through a broad valley that is filled with very permeable sand and gravel. The basin has a large ground-water storage capacity and, consequently, the river maintains a high sustained flow. The Hocking Rver locally contains outwash in and along its floodplain, which provides a substantial amount of ground-water runoff. Above Columbus, the Scioto River crosses thin layers of limestone that crop out along the stream valley, and the adjacent uplands are covered with glacial till; ground-water runoff from this reach is relatively small. Immediately south of Columbus, however, the Scioto Valley widens and is filled with coarse outwash (see figure 3-18). The reason that Mad River has a higher low-flow index than the Scioto River at Chillicothe is because the Mad River receives ground-water runoff throughout its entire length, while the flow of the Scioto River increases significantly only in the southern part of the basin, that is, in the area of outwash south of Columbus.

Whiteoak and Home Creeks originate in bedrock areas where relatively thin alternating layers of sandstone, shale, and limestone crop out along the hill sides. The greater relief in these basins promotes surface runoff and the rocks are not very permeable. Obviously the ground-water storage characteristics and potential yield of these basins are far less than those filled or partly filled with outwash.

Figure 3-22 shows a geologic map of a part of southern Mississippi and northern Louisiana. Notice that gaging stations 1, 2, and 3 record the drainage from the Citronelle Formation, while stations 4, 5, and 6 represent the drainage from the older rocks. Respective flow-duration curves, illustrated in Figure 3-23, show that stations 1 and 2 have high low-flow indices, with station 3 a relatively close third. The high flow-duration indices indicate that the Citronelle Formation has a greater ground-water storage capacity, a higher rate of natural recharge, and presumably would provide larger yields to wells than the underlying strata. This formation

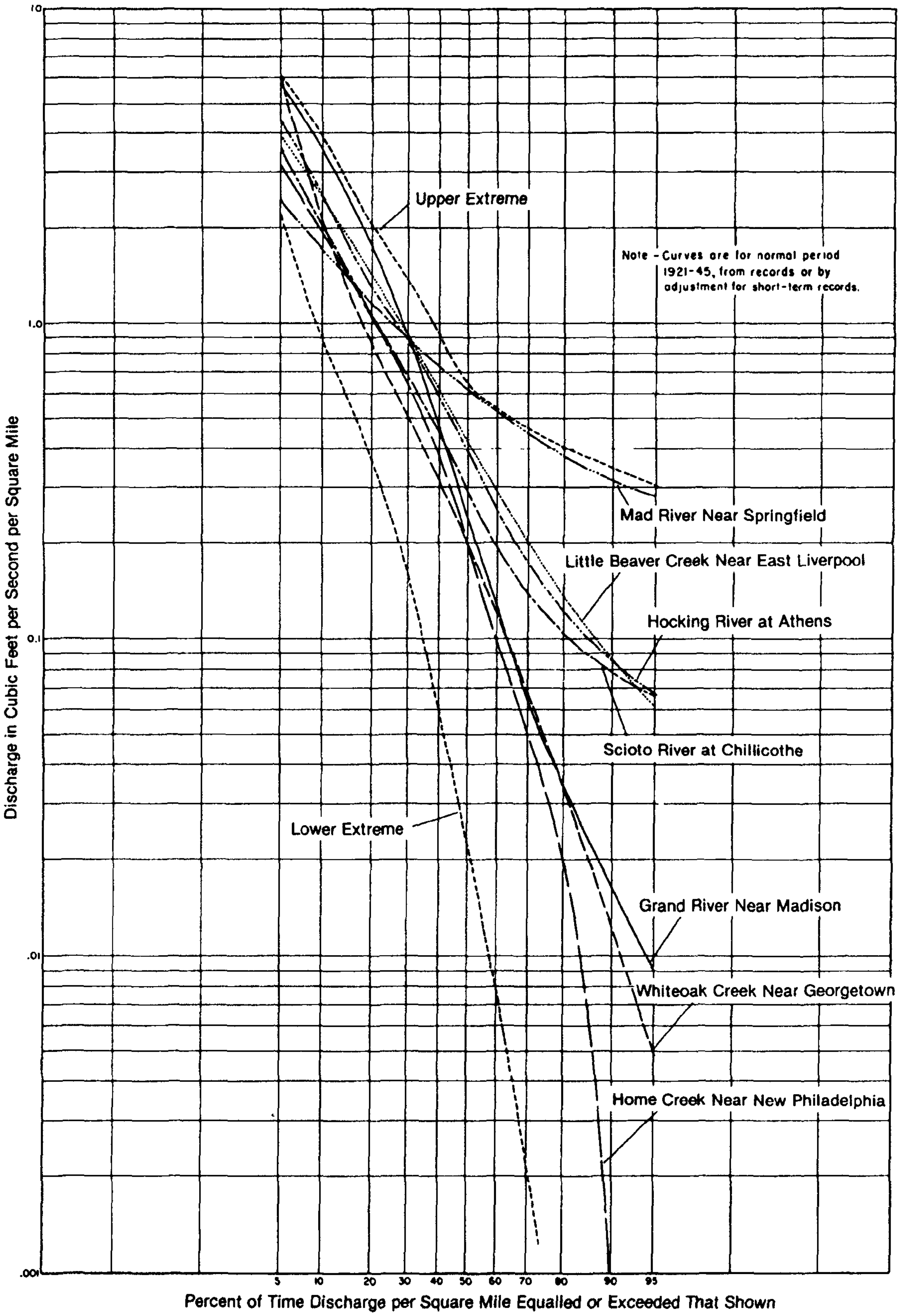


Figure 3-21. Flow-Duration Curves for Selected Ohio Streams

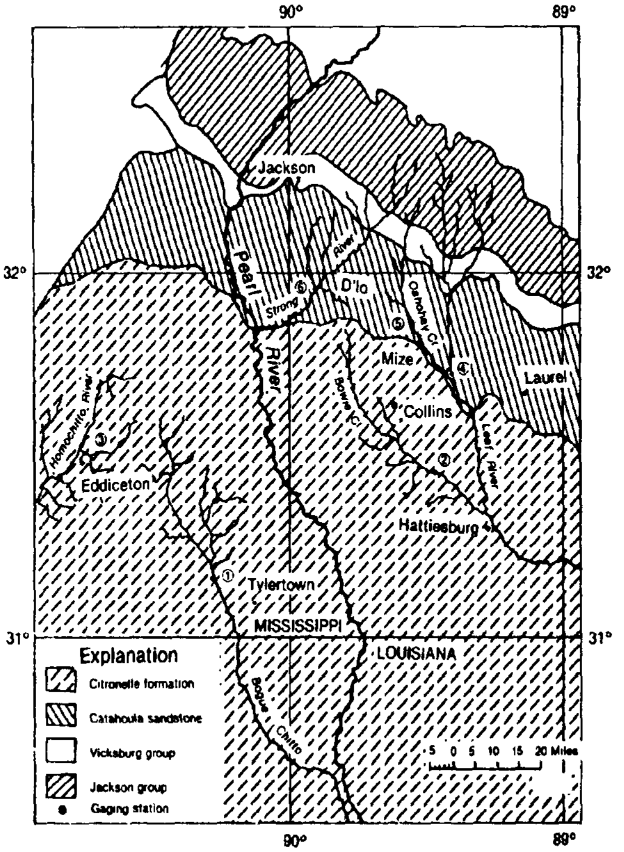


Figure 3-22. Geologic Map of Area in Southern Mississippi Having Approximately Uniform Climate and Altitude

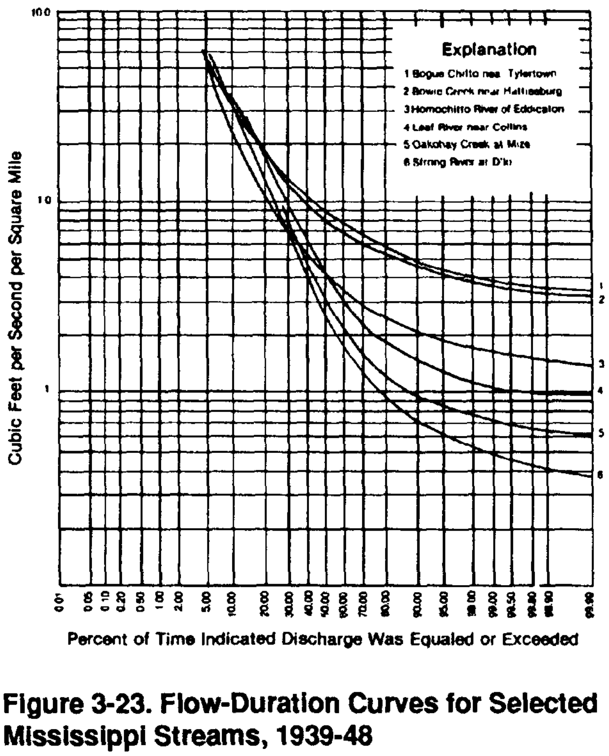


Figure 3-23. Flow-Duration Curves for Selected Mississippi Streams, 1939-48

consists of sand, gravel, and clay, while the other strata are generally composed of finer materials. Thus it would appear that streamflow data can be used as an aid to a better understanding of the permeability and infiltration capacity, as well as facies changes, of geologic units.

Flow Ratios

Walton (1970) reported that grain-size frequency distribution curves are somewhat analogous to flow-duration curves in that their shapes are indicative of water-yielding properties of deposits. He pointed out that a measure of the degree to which all of the grains approach one size, and therefore, the slope of the grain-size frequency distribution curve, is the sorting. One parameter of sorting is obtained by the ratio $(D25/D75)^{1/2}$. Walton modified this equation by replacing the 25 and 75 percent grain-size diameters with the 25 and 75 percent flow. In this case a low ratio is indicative of a permeable basin or one that has a large ground-water storage capacity.

The Q25 and Q75 data are easily obtainable from flow-duration curves. Using the data from Figure 113, Mad River has a flow ratio of 1.58 and the Scioto River's ratio is 2.58, while Home Creek, typifying a basin of low permeability, has the highest ratio which is 5.16.

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Chapter 4

BASIC HYDROGEOLOGY

Introduction

Hydrogeology is the study of ground water, its origin, occurrence, movement, and quality. Ground water is a part of the hydrologic cycle and it reacts in concert with all of the other parts. Therefore, it is essential to have some knowledge of the components, particularly precipitation, infiltration, and the relation between ground water and streams, as well as the impact of the geologic framework on water resources. This chapter provides a brief outline of these topics and interactions.

Precipitation

Much precipitation never reaches the ground; it evaporates in the air and from trees and buildings. That which reaches the land surface is variable in time, areal extent, and intensity. The variability has a direct impact on streamflow, evaporation, transpiration, soil moisture, ground-water recharge, ground water, and ground-water quality. Therefore, precipitation should be examined first in any hydrogeologic study in order to determine how much is available, its probable distribution, and when and under what conditions it is most likely to occur. In addition, a determination of the amount of precipitation is the first step in a water-balance calculation.

Seasonal Variations in Precipitation

Throughout much of the United States, the spring months are most likely to be the wettest owing to the general occurrence of rains of low intensity that often continue for several days at a time. The rain, in combination with springtime snowmelt, will saturate the soil, and streamflow is generally at its peak over a period of several weeks or months. Because the soil is saturated, this is the major period of ground-water recharge. In addition, since much of the total runoff consists of precipitation and snowmelt (surface runoff), streams most likely will contain less dissolved mineral matter than at any other time during the year.

Not uncommonly, the fall also is a wet period, although precipitation is not as great or prolonged as during the spring. Because ground-water recharge can occur over wide areas during spring and fall, one should expect some natural changes in the chemical quality of ground water in surficial or shallow aquifers.

During the winter in northern states, the ground is frozen, largely prohibiting infiltration and ground-water recharge. An early spring thaw coupled with widespread precipitation may lead to severe flooding over large areas.

Types of Precipitation

Precipitation is classified by the conditions that produce a rising column of unsaturated air, which is antecedent to precipitation. The major conditions are convective, orographic, and cyclonic.

Convectional precipitation is the result of uneven heating of the ground, which causes the air to rise, expand, the vapor to condense, and precipitation to occur. Much of the summer precipitation is convective, that is, high intensity, short duration storms that are usually of small areal extent. They often cause flash floods in small basins. Most of the rain does not infiltrate, usually there is a soil-moisture deficiency, and ground-water recharge is likely to be of a local nature. On the other hand, these typically small, local showers can have a significant impact on shallow ground-water quality because some of the water flows quickly through fractures or other macropores, carrying water-soluble compounds leached from the dry soil to the water table. In cases such as these, the quality of shallow ground water may be impacted as certain chemical constituents, and perhaps microbes as well, may increase dramatically within hours (see Chapter 5).

Orographic precipitation is caused by topographic barriers that force the moisture-laden air to rise and cool. This occurs, for example, in the Pacific Northwest, where precipitation exceeds 100 inches per year, and in Bangladesh, which receives more than 425 inches per year, nearly all of which falls during the monsoon season. In this vast alluvial plain, rainfall commonly averages 106 inches during June for a daily average exceeding 3.5 inches.

Cyclonic precipitation is related to large low pressure systems that require 5 or 6 days to cross the United States from the northwest or Gulf of Mexico. These systems are the major source of winter precipitation. During the spring, summer, and fall, they lead to rainy periods that may last 2 or 3 days or more. They are characterized by low intensity and long duration, and cover a wide area. They probably have a major impact on natural recharge to shallow ground-water systems during the summer and fall, and influence ground-water quality as well.

Recording Precipitation

Precipitation is measured by recording and nonrecording rain gages. Many are located throughout the country but because of their inadequate density, estimates of annual, and particularly summer, precipitation probably are too low. Records can be obtained from Climatological Data, which are published by the National Oceanic and Atmospheric Administration (NOAA). Precipitation is highly variable, both in time and space. The areal extent is evaluated by means of contour or isohyet maps (fig. 4-1).

A rain gage should be installed in the vicinity of a site under investigation in order to know exactly when precipitation occurred, how much fell, and its intensity. Data such as these are essential to the interpretation of hydrographs of both wells and streams, and they provide considerable insight into the causes of fluctuations in shallow ground-water quality.

Infiltration

The variability of streamflow depends on the source of the supply. If the source of streamflow is from surface runoff, the stream will be characterized by short periods of high flow and long periods of low flow or no flow at all. Streams of this type are known as "flashy." If the basin is permeable, there will be little surface runoff and ground water will provide the stream with a high sustained, uniform flow. These streams are known as "steady." Whether a stream is steady or flashy depends on the infiltration of precipitation and snowmelt.

When it rains, some of the water is intercepted by trees or buildings, some is held in low places on the ground (depression storage), some flows over the ground to a stream (surface runoff), some is evaporated, and some infiltrates. Of the water that infiltrates, a part replenishes the soil-moisture deficiency, if any, while the remainder percolates deeper, perhaps becoming ground water. The depletion of soil moisture begins immediately after a rain due to evaporation and transpiration.

Infiltration capacity (f) is the maximum rate at which a soil is capable of absorbing water in a given condition. Several factors control infiltration capacity.

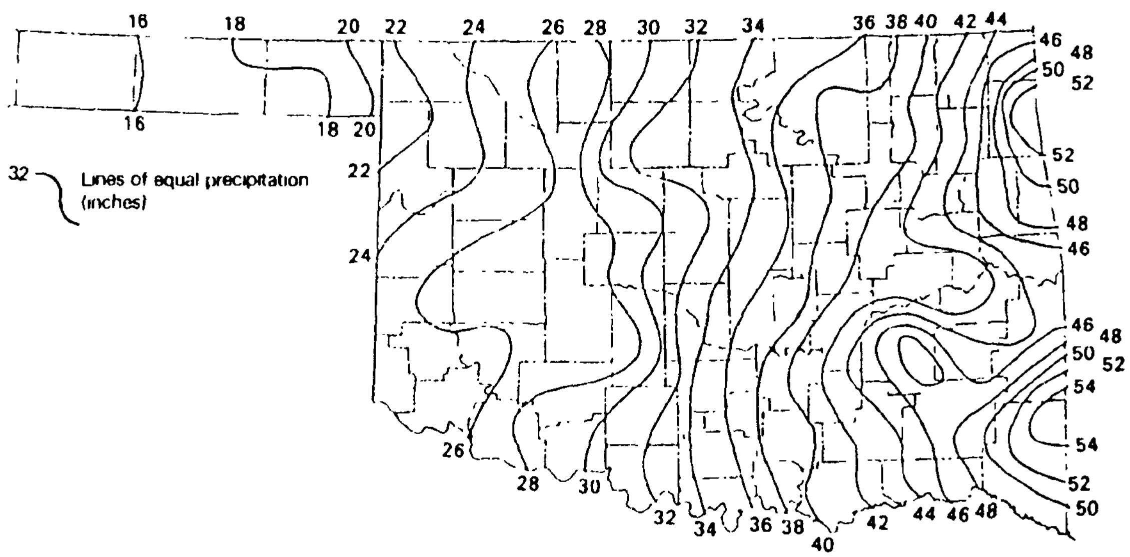

Figure 4-1. Distribution of Annual Average Precipitaiton in Oklahoma, 1970-79 (from Pettyjohn and others, 1983)

o Antecedent rainfall and soil-moisture conditions. Soil moisture fluctuates seasonally, usually being high during winter and spring and low during the summer and fall. If the soil is dry, wetting the top of it will create a strong capillary potential just under the surface, supplementing gravity. When wetted, the clays forming the soil swell, which reduces the infiltration capacity shortly after a rain starts.

o Compaction of the soil due to raindrop impact.

o Inwash of fine material into soil openings, which reduces infiltration capacity. This is especially important if the soil is dry.

o Compaction of the soil by animals, roads, trails, urban development, etc.

o Certain microstructures in the soil will promote infiltration, such as soil structure, openings caused by burrowing animals, insects, decaying rootlets and other vegetative matter, frost heaving, desiccation cracks, and other macropores.

o Vegetative cover, which tends to increase infiltration because it promotes populations of burrowing organisms and retards surface runoff, erosion, and compaction by raindrops.

o Decreasing temperature, which increases water viscosity, reducing infiltration.

o Entrapped air in the unsaturated zone, which tends to reduce infiltration.

o Surface gradient.

Infiltration capacity is usually greater at the start of a rain that follows a dry period, but it decreases rapidly (fig. 4- 2). After several hours it is nearly constant because the soil becomes clogged by particles and swelling clays. A sandy soil, as opposed to a clay-rich soil, may maintain a high infiltration capacity for a considerable time.

As the duration of rainfall increases, infiltration capacity continues to decrease. This is partly due to the increasing resistance to flow as the moisture front moves downward; that is, the resistance is a result of frictional increases due to the increasing length of flow channels and the general decrease in permeability owing to swelling clays. If precipitation is greater than infiltration capacity, surface runoff occurs. If precipitation is less than the infiltration capacity, all moisture is absorbed.

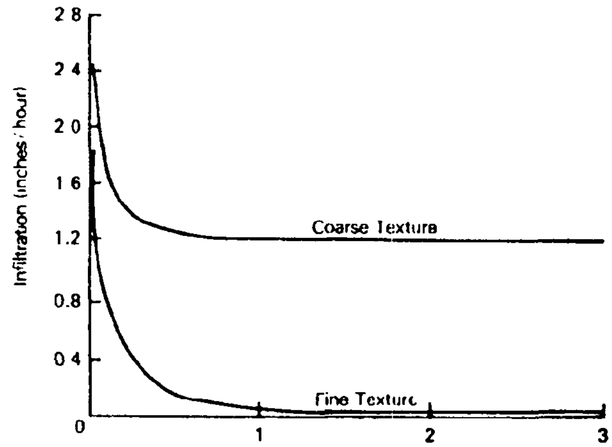

Figure 4-2. Infiltration Capacity Decreases with Time During a Rainfall Event

When a soil has been saturated by water then allowed to drain by gravity, the soil is said to be holding its field capacity of water. (Many investigators are opposed to the use and definition of the term field capacity because it does not account for the rapid flow of water through preferred paths, such as macropores.) Drainage generally requires no more than two or three days and most occurs within one day. A sandy soil has a low field capacity that is reached quickly; clay-rich soils are characterized by a high field capacity that is reached slowly (fig. 4-3).

The water that moves down becomes ground-water recharge. Since recharge occurs even when field

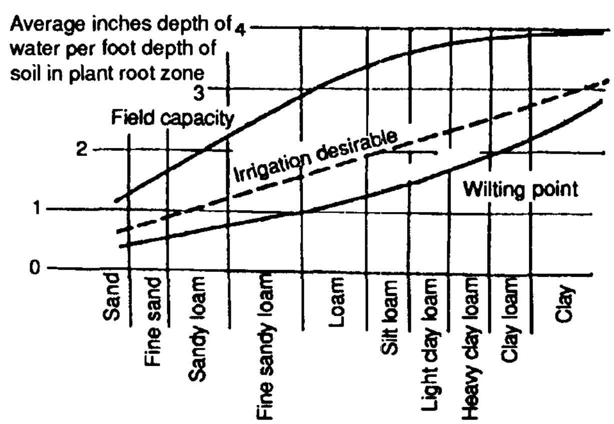

Figure 4-3. Relation Between Grain Size and Field Capacity and Wilting Point

capacity is not reached, there must be a rapid transfer of water through the unsaturated zone. This probably occurs through macropores (Pettyjohn, 1982). Figure 4-4 is a graph of the water table following a storm that provided slightly more than three inches of rain in about an hour in mid-July in north-central Oklahoma. At that time the water table in a very fine-grained aquifer was about 7.5 feet below land surface. Notice that the water table began to rise within a half hour of the start of the rain despite the very low soil-moisture content. The velocity of the infiltrating water through the unsaturated zone was about 15 feet per hour, and this only could have occurred by flow through fractures and other macropores. Clearly field capacity could not have been reached in this short period of time.

Surface Water

Streamflow, runoff, discharge, and yield of drainage basin are all nearly synonymous terms. Channel storage refers to all of the water contained at any instant within the permanent stream channel. Runoff includes all of the water in a stream channel flowing past a cross section; this water may consist of precipitation that falls directly into the channel, surface runoff, ground-water runoff, and effluent.

Although the total quantity of precipitation that falls directly into the channel may be large, it is quite small in comparison to the total flow. Surface runoff, including interflow or stormflow, is the only source of water in ephemeral streams and intermittent streams during part of the year. It is the major cause of flooding. During dry weather, ground-water runoff may account for the entire flow of a stream. It is the major source of water to streams from late summer to winter; at this time streams also are most highly mineralized under natural conditions. Ground water moves slowly to the stream, depending on the hydraulic gradient and permeability; the contribution is slow but the supply is steady. When ground-water runoff provides a stream's entire discharge, the flow is called dry-weather or base flow. Other sources of runoff include the discharge of industrial or municipal effluent or irrigation return flow.

Rates of Flow

Water courses are generally classified on the basis of their length, size of drainage basin, or discharge; the latter is probably the most significant index of a stream's utility in a productive society. Rates of flow generally are reported as cubic feet per second (cfs), millions of gallons per day (mgd), acre-feet per day, month, or year, cfs per square mile of drainage basin (cfs/mi^2), or inches depth on drainage basin per day, month, or year. In the United States, the most common unit of measurement is cfs. The discharge (Q) is determined by measuring the cross-sectional area of the channel (A), in square feet, and the average velocity of the water (v), in feet per second, so that:

$$Q=vA \quad (9)$$

Stream Discharge Measurements and Records

At a stream gaging site the discharge is measured periodically at different rates of flow, which are plotted against the elevation of the water level in the stream (stage or gage-height). This forms a rating curve (fig. 4-5). At a gaging station the stage is continuously

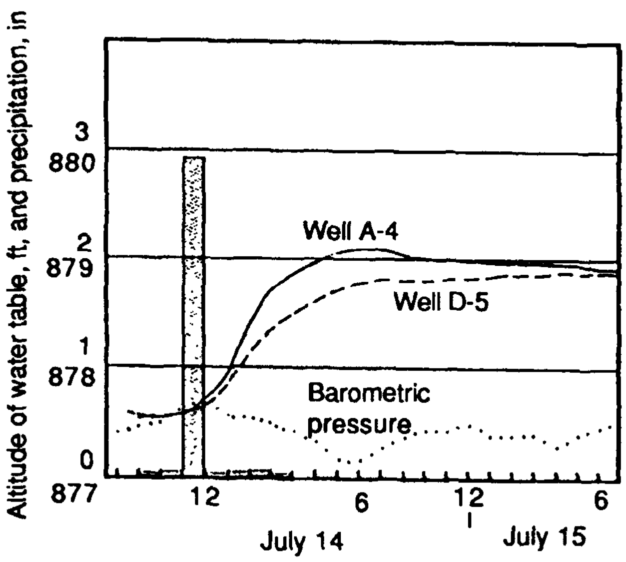

Figure 4-4. Response of the Water Table in a Fine-Grained, Unconfined Aquifer to a High Intensity Rain

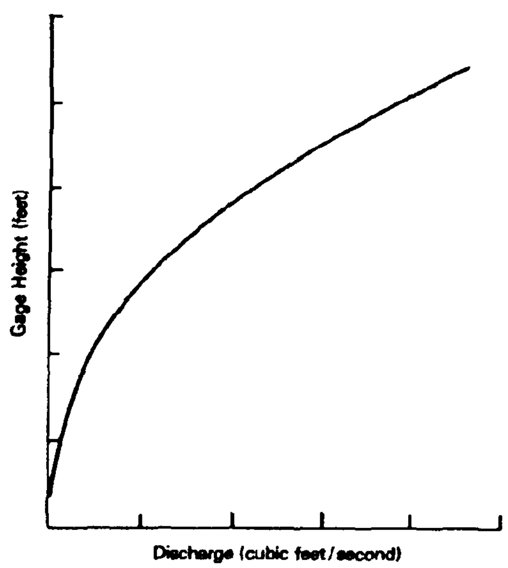

Figure 4-5. A Generalized Stream Stage vs. Discharge Rating Curve

measured and this record is converted, by means of the rating curve, into a discharge hydrograph. The terminology used to describe the various parts of a stream hydrograph are shown in Figure 4-6.

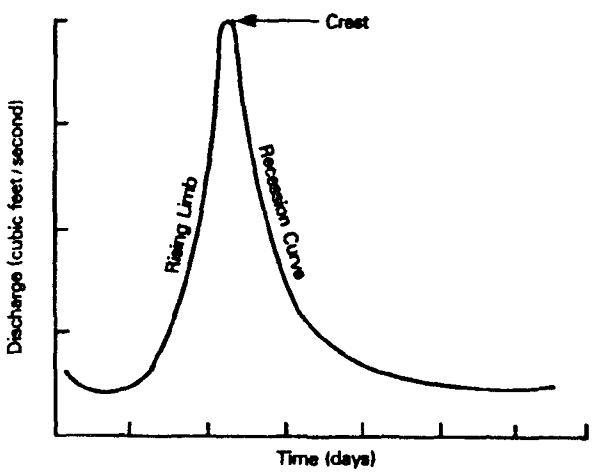

Figure 4-6. Stream Hydrograph Showing Definition of Terms

Discharge, water quality, and ground-water level records are published annually by the U. S. Geological Survey for each state. An example of the annual record of a stream is shown in Figure 4-7. Notice that these data are reported in "water years." The water year is designated by the calendar year in which it ends, which includes 9 of the 12 months. Thus, water year 1990 extends from October 1, 1989, to September 30, 1990.

The Relation between Ground Water and Surface Water

There are many tools for learning about ground water without basing estimates on the ground-water system itself, and one approach is the use of streamflow data (See Chapter 3). Analyses of streamflow data permit an evaluation of the basin geology, permeability, the amount of ground-water contribution, and the major areas of discharge. In addition, if chemical quality data are available or collected for a specific stream, they can be used to determine background concentrations of various parameters and locate areas of ground-water contamination as well.

Ground Water

The greatest difficulty in working with ground water is that it is hidden from view, cannot be adequately tested, and occurs in a complex environment. On the other hand, the general principles governing ground-water occurrence, movement, and quality are quite well known, which permits the investigator to develop a reasonable degree of confidence in his predictions. The experienced investigator is well aware, however, that these predictions are only estimates of the manner in which the system functions. Ground-water hydrology is not an exact science, but it is possible to develop a good understanding of a particular system if one pays attention to fundamental principles.

The Water Table

Water under the surface of the ground occurs in two zones, an upper unsaturated zone and the deeper saturated zone (fig. 4-8). The boundary between the two zones is the water table. In the unsaturated zone, most of the open spaces are filled with air, but water occurs as soil moisture and in a capillary fringe that extends upward from the water table. Water in the unsaturated zone is under a negative hydraulic pressure, that is, it is less than atmospheric. Ground water occurs below the water table and all of the pores and other openings are filled with fluid that is under pressure greater than atmospheric.

In a general way, the water table conforms to the surface topography, but it lies at a greater depth under hills than it does under valleys (fig. 4-8). In general, in humid and semiarid regions the water table lies at depths ranging from 0 to about 20 feet or so, but its depth exceeds hundreds of feet in some desert environments.

The elevation and configuration of the water table must be determined with care, and many such measurements have been incorrectly taken. The position of the water table can be determined from the water level in swamps, flooded excavations (abandoned gravel pits, highway borrow pits, etc.), sumps in basements, lakes, ponds, streams, and shallow wells. In some cases there may be no water table at all or it may be seasonal.

Measurement of the water level in drilled wells, particularly if they are of various depths, will more likely reflect the pressure head of one or more aquifers that are confined than the actual water table.

Figure 4-9 illustrates the difference in water levels in several wells, each of which is of a different depth. Purposely no scale has been applied to the sketch because the drawing is relative. That is, the same principle exists regardless of scale, and individual zones could be only a few inches or feet thick, or they might exceed several tens of feet. Notice that each well has a different water level but the water table can be determined only in Well 2. Wells 1, and 3-5, which tap confined aquifers, are deeper and each is screened in

ARKANSAS RIVER BASIN

07176500 BIRD CREEK NEAR AVANT, OK

LOCATION.--Lat 36°29'12", long 96°03'50", in SW 1/4 NW 1/4 sec.7 (revised), T.23 N., R.12 E., Osage County, Hydrologic Unit 11070107, 150 ft upstream from county road bridge at Avant, 1.5 mi upstream from Candy Creek, and at mile 54.2.

DRAINAGE AREA.--364 mi^2.

PERIOD OF RECORD.--August 1945 to current year.

GAGE.--Water-stage recorder. Datum of gage is 651.28 ft above National Geodetic Vertical Datum of 1929.

REMARKS.--Records fair. Several unpublished observations of water temperature, specific conductance, and pH were made during the year and are available at the District Office. Flow slightly regulated since 1958 by Bluestem Lake. Some regulation since March 1977 by Birch Lake (station 07176460), located on Birch Creek, 12.1 mi upstream. Small diversions upstream for municipal water supply for the cities of Pawhuska and Barnsdall.

AVERAGE DISCHARGE.--43 years, 221 ft^3/s, 160,100 acre-ft/yr.

EXTREMES FOR PERIOD OF RECORD.--Maximum discharge, 32,400 ft^3/s, Oct. 2, 1959, gage height, 31.40 ft; maximum gage height, 32.03 ft, Mar. 11, 1974; no flow at times.

EXTREMES FOR CURRENT YEAR.--Peak discharges greater than base discharge of 6,000 ft^3/s and maximum (*):

Date	Time	Discharge (ft^3/s)	Gage Height (ft)	Date	Time	Discharge (ft^3/s)	Gage Height (ft)
Nov. 24	1615	8,270	11.25	Mar. 3	1215	6,390	8.77
Dec. 19	2115	9,820	13.65	Apr. 1	2045	*16,200	*23.47

Minimum daily discharge, 3.1 ft^3/s, Oct. 17, 18.

DISCHARGE, CUBIC FEET PER SECOND, WATER YEAR OCTOBER 1987 TO SEPTEMBER 1988
MEAN VALUES

DAY	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1	416	14	157	457	101	69	13200	146	12	8.8	36	16
2	332	13	131	341	101	522	7040	144	142	9.6	30	17
3	303	12	115	297	120	4680	922	137	52	20	27	20
4	285	12	92	257	81	1460	633	133	55	22	21	17
5	277	12	45	163	118	1860	813	129	46	24	20	16
6	268	10	40	138	107	1890	711	125	26	24	16	16
7	234	10	36	132	105	1520	662	120	23	22	16	14
8	132	10	29	120	106	898	629	120	21	18	16	11
9	21	10	26	81	114	638	608	120	19	16	16	9.8
10	7.0	10	23	120	116	534	2180	108	17	16	16	9.6
11	6.3	10	20	120	111	478	1090	91	16	22	16	9.6
12	6.2	9.8	15	120	104	349	645	54	16	112	15	9.6
13	5.8	9.6	14	142	102	322	404	35	16	62	15	9.6
14	5.6	9.6	20	165	62	268	311	28	16	34	15	9.6
15	4.8	80	30	165	43	156	252	22	16	26	15	9.6
16	3.8	93	47	923	41	137	152	21	15	22	15	146
17	3.1	94	52	1540	41	170	145	23	12	34	15	208
18	3.1	51	141	519	42	555	2570	24	11	26	15	1410
19	3.3	36	5400	1020	175	405	831	24	11	234	15	1540
20	3.6	26	4770	785	212	333	484	24	11	158	15	450
21	4.1	16	943	397	147	272	383	24	11	50	15	219
22	4.7	10	778	344	117	232	317	24	11	41	15	160
23	8.5	8.2	595	253	96	209	186	29	11	31	15	327
24	9.6	3370	525	221	80	196	157	33	11	27	15	268
25	8.3	1450	876	191	73	188	200	59	11	26	16	168
26	7.6	336	1110	129	70	175	220	41	11	24	16	108
27	7.4	207	2160	91	69	170	200	29	10	22	16	80
28	8.4	227	1540	120	69	166	166	20	10	27	16	66
29	9.6	240	758	120	69	553	151	18	10	277	16	61
30	9.6	200	752	146	---	528	146	17	9.6	123	16	54
31	13	---	938	120	---	1170	---	15	---	56	16	---
TOTAL	2411.4	6596.2	22178	9737	2792	21103	36408	1937	658.6	1614.4	537	5459.4
MEAN	77.8	220	715	314	96.3	681	1214	62.5	22.0	52.1	17.3	182
MAX	416	3370	5400	1540	212	4680	13200	146	142	277	36	1540
MIN	3.1	8.2	14	81	41	69	145	15	9.6	8.8	15	9.6
AC-FT	4780	13080	43990	19310	5540	41860	72220	3840	1310	3200	1070	10830

CAL YR 1987 TOTAL 123598.2 MEAN 339 MAX 7340 MIN 3.1 AC-FT 245200
WTR YR 1988 TOTAL 111432.0 MEAN 304 MAX 13200 MIN 3.1 AC-FT 221000

Figure 4-7. Stream Discharge Record for Bird Creek near Avant, Oklahoma (From U.S. Geological Survey Water Resources Data for Oklahoma Water Year 1987, p. 90)

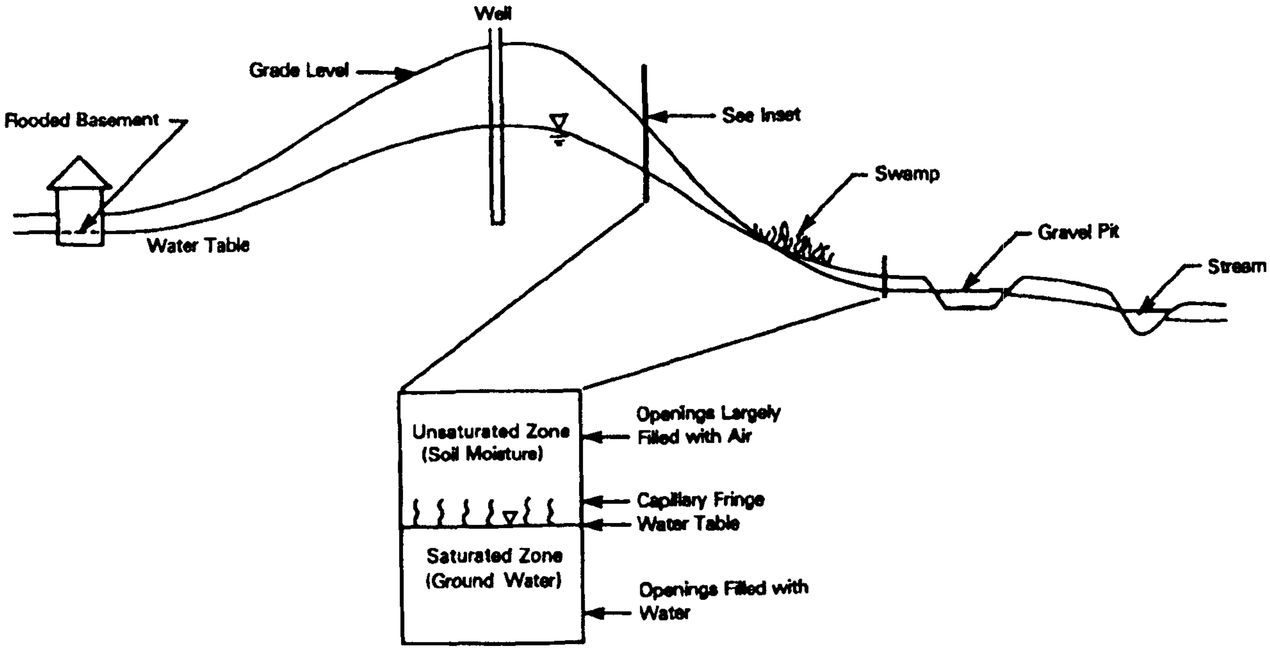

Figure 4-8. The Water Table Generally Conforms to the Surface Topography

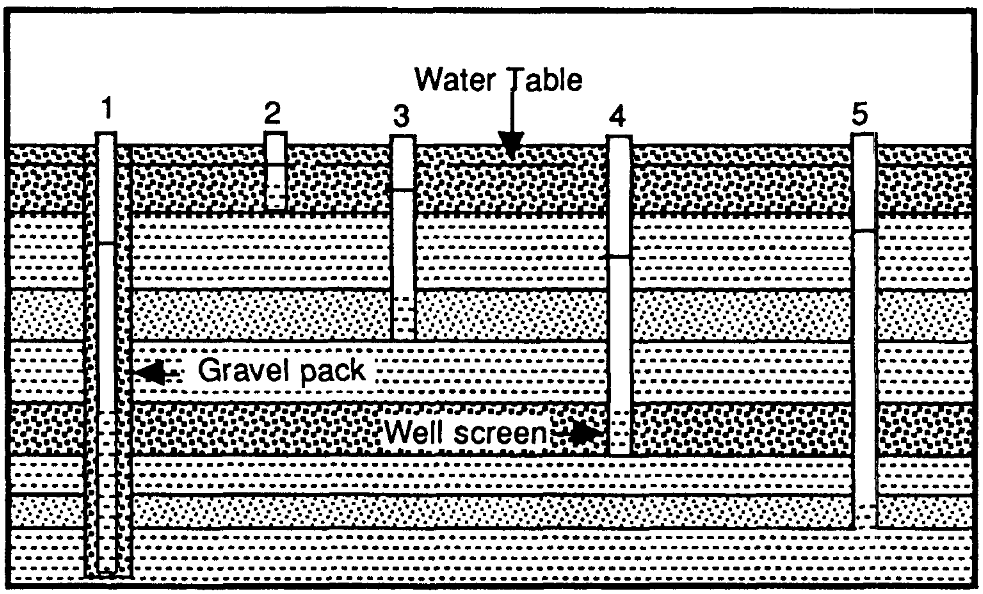

Figure 4-9. The Water Level in a Well Indicates the Pressure that Exists in the Aquifer that It Taps

a particular permeable zone that is bounded above and below by less permeable confining units. The water level in each well reflects the pressure that exists in the individual zone that is tapped by the well. A different situation occurs in Well 1, because the gravel pack surrounding the well casing and screen provides a high permeability conduit that connects all of the water-bearing zones. The water level in Well 1 is a composite of the pressure in all of the zones.

Because hydraulic head generally differs with depth, it is exceedingly important to pay attention to well depth and construction details when preparing water-level maps and determining hydraulic gradient and flow direction.

For example, water-level measurements in wells 1 and 2 or 5 and 4 would suggest a gradient to the left, but wells 2 and 3 or 3 and 4 would allude a gradient to the right of the drawing. In addition, the apparent slope of the gradient would depend on the wells being measured.

Accurately determining the position of the water table is important not only because of the need to determine the direction and magnitude of the hydraulic gradient, but, in addition, the thickness, permeability, and composition of the unsaturated zone exert a major control on ground-water recharge and the movement of contaminants from land surface to an underlying aquifer. Attempting to ascertain the position of the water table by measuring the water level in drilled wells nearly always will incorrectly suggest an unsaturated zone that is substantially thicker than actually is the case, and thus may provide a false sense of security.

Ground water has many origins, however, all fresh ground water originated from precipitation that infiltrated. Magmatic or juvenile water is "new" water that has been released from molten igneous rocks. The steam that is so commonly given off during volcanic eruptions is probably not magmatic, but rather shallow ground water heated by the molten magma. Connate water is defined as that entrapped within sediments when they were deposited. Ground water, however, is dynamic and probably in only rare circumstances does connate water meet this definition. Rather, the brines that underlie all or nearly all fresh ground water have changed substantially through time because of chemical reactions with the geologic framework.

Aquifers and Confining Units

In the subsurface, rocks serve either as confining units or aquifers. A confining unit or aquitard is characterized by low permeability that does not readily permit water to pass through it. Confining units do, however, store large quantities of water. Examples include shale, clay, and silt. An aquifer has sufficient permeability to permit water to flow through it with relative ease and, therefore, it will provide a usable quantity to a well or spring.

Water occurs in aquifers under two different conditions—unconfined and confined (fig. 4-10). An unconfined or water-table aquifer has a free water surface that rises and falls in response to differences between recharge and discharge. A confined or artesian aquifer is overlain and underlain by aquitards and the water is under sufficient pressure to rise above the base of the confining bed, if it is perforated. In some cases, the water is under sufficient pressure to rise above land surface. These are called flowing or artesian wells. The water level in an unconfined aquifer is *referred* to as the water table; in *confined aquifers* the water level is called the potentiometric surface.

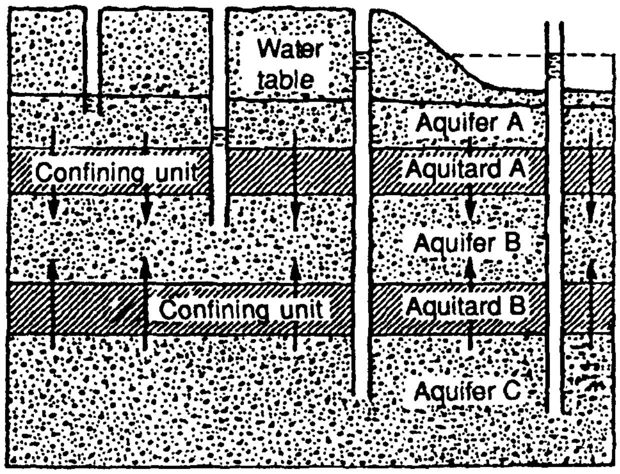

Figure 4-10. Aquifer A is Unconfined and Aquifers B and C are Confined, but Water May Leak Through Confining Units to Recharge Adjacent Water-Bearing Zones

Water will arrive at some point in an aquifer through one or several means. The major source is direct infiltration of precipitation, which occurs nearly everywhere. Where the water table lies below a stream or canal, the surface water will infiltrate. This source is important part of the year in some places (intermittent streams) and is a continuous source in others (ephemeral or losing streams). Interaquifer leakage, or flow from one aquifer to another, is probably the most significant source in deeper, confined aquifers. Likewise, leakage from aquitards is very important where pumping from adjacent aquifers has lowered the head or potentiometric surface sufficiently for leakage to occur. Underflow, which is the normal movement of water through an aquifer, also will transmit ground water to a specific point. Additionally, water can reach an aquifer through artificial means, such as leakage from ponds, pits, and lagoons, from sewer lines, and from dry wells, among others.

An aquifer serves two functions, one as a conduit through which flows occurs, and the other as a storage reservoir. This is accomplished by means of openings in the rock. The openings include those between individual grains and those present in joints, fractures, tunnels, and solution openings. There are also artificial openings, such as engineering works, abandoned wells, and mines. The openings are primary if they were formed at the time the rock was deposited and secondary if they developed after lithification. Examples of the latter include fractures and solution openings.

Porosity and Hydraulic Conductivity

Porosity, expressed as a percentage or decimal fraction, is the ratio between the openings and the total rock volume. It defines the amount of water a saturated rock volume can store. If a unit volume of saturated rock is allowed to drain by gravity, not all of the water it contains will be released. The volume drained is the specific yield, a percentage, and the volume retained is the specific retention. Related to the attraction between water and earth materials, specific retention generally increases as sorting and grain size decrease. Porosity determines the total volume of water that a rock unit can store, while specific yield defines the amount that is available to wells. Porosity is equal to the sum of specific yield and specific retention. Typical values for various rock types are listed in Table 4-1.

Permeability (P) is used in a qualitative sense, while hydraulic conductivity (K) is a quantitative term. They are expressed in a variety of units gpd/ft^2 (gallons per day per square foot) will be used in this section; see Table 4-2 for conversion factors) and both refer to the ease with which water can pass through a rock unit. It is the hydraulic conductivity that allows an aquifer to serve as a conduit. Hydraulic conductivity values range widely from one rock type to another and even within the same rock. It is related to grain size, sorting, cementation, and the amount of secondary openings, among others. Typical ranges in values of hydraulic conductivity for most common water-bearing rocks are shown in Table 4-3 and Figure 4-11.

Material	Porosity	Specific Yield (% by vol)	Specific Retention
Soil	55	40	15
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone, semiconsolidated	11	6	5
Granite	0.1	0.09	0.01
Basalt, young	11	8	3

Table 4-1. Average Porosity, Specific Yield, and Specific Retention Values for Selected Earth Materials

Those rocks or aquifers in which the hydraulic conductivity is nearly uniform are called homogeneous and those in which it is variable are heterogeneous or nonhomogeneous. Hydraulic conductivity also can vary horizontally in which case the aquifer is anisotropic. If uniform in all directions, which is rare, it is isotropic. The fact that both unconsolidated and consolidated sedimentary strata are deposited in horizontal units is the reason that hydraulic conductivity is generally greater horizontally than vertically, commonly by several orders of magnitude.

Hydraulic Gradient

The hydraulic gradient (I) is the slope of the water table or potentiometric surface, that is, the change in water level per unit of distance along the direction of maximum head decrease. It is determined by measuring the water level in several wells. The water level in a well (fig. 4-12), usually expressed as feet above sea level, is the total head (ht), which consists of elevation head (z) and pressure head (hp).

$$ht=z+hp \quad (10)$$

The hydraulic gradient is the driving force that causes ground water to move in the direction of maximum decreasing total head. It is generally expressed in consistent units, such as feet per foot. For example, if the difference in water level in two wells 1000 feet apart is 2 feet, the gradient is 2/1,000 or 0.002 (fig. 4-13). Since the water table or potentiometric surface is a plane, the direction of ground-water movement and the hydraulic gradient must be determined by information from three wells (fig. 4-14). The wells must tap the same aquifer, and should be of similar depth and screened interval.

Using the three point method, water-level elevations are determined for each well, and their locations are plotted on a map. Lines are drawn to connect the wells in such a way that a triangle is formed. Using the elevations of the end points, each line is divided into a number of equal elevation segments. Selecting points of equal elevation on two of the lines, equipotential or potentiometric contours are drawn through the points. A flow line is then constructed so that it intersects the

Hydraulic Conductivity (K)

Meters per day ($m\ d^{-1}$)	Centimeters per second ($cm\ s^{-1}$)	Feet per day ($ft\ d^{-1}$)	Gallons per day per square foot ($gal\ d^{-1}\ ft^{-2}$)
1	1.16×10^{-3}	3.28	2.45×10^{1}
8.64×10^{2}	1	2.83×10^{3}	2.12×10^{4}
3.05×10^{-1}	3.53×10^{-4}	1	7.48
4.1×10^{-2}	4.73×10^{-5}	1.34×10^{-1}	1

Transmissivity (T)

Square meters per day ($m^2\ d^{-1}$)	Square feet per day ($ft^2\ d^{-1}$)	Gallons per day per foot ($gal\ d^{-1}\ ft^{-1}$)
1	10.76	80.5
.0929	1	7.48
.0124	.134	1

Recharge Rates

Unit depth per year	Volume ($m^3\ d^{-1}\ km^{-2}$)	Volume ($ft^3\ d^{-1}\ mi^{-2}$)	Volume ($gal\ d^{-1}\ mi^{-2}$)
(In millimeters)	2.7	251	1,874
(In inches)	70	6,365	47,748

Flow Rates

($m^3\ s^{-1}$)	($m^3\ min^{-1}$)	($ft^3\ s^{-1}$)	($ft^3\ min^{-1}$)	($gal\ min^{-1}$)
1	60.	35.3	2,120	15,800
.0167	1	.588	35.3	264
.0283	1.70	1	60	449
.000472	.0283	.0167	1	7.48
.000063	.00379	.0023	.134	1

Table 4-2. Conversion Factors for Hydraulic Conductivity, Recharge Rates, and Flow Rates

Material	Hydraulic conductivity (rounded values) (ft/day)	[(gal/day)/ft²]	(meters/day)
Coarse sand	200	1500	60
Medium sand	130	1000	40
Silt	1	5	0.2
Clay	0.001	0.01	0.0004
Limestone (Castle Hayne)	300	2000	80
Saprolite	5	50	2
Granite and gneiss	5	50	2
Slate	3	25	1

Table 4-3. Hydraulic Conductivity of Selected Rocks (Heath, 1980)

equipotential contours at a right angle. Ground water flows in the direction of decreasing head or water level.

Potentiometric Surface Maps and Flow Nets

Potentiometric surface or water-level maps are an essential part of any ground-water investigation because they indicate the direction in which ground water is moving and provide an estimate of the hydraulic gradient, which controls velocity. A potentiometric surface map is a graphical representation of the hydraulic gradient. They are prepared by plotting water-level measurements on a base map and then contouring them. The map should be drawn so that it actually reflects the hydrogeological conditions. Sample map is shown in Figure 4-15.

The water-level contours are called potentiometric lines, indicating that the water has the potential to rise to that

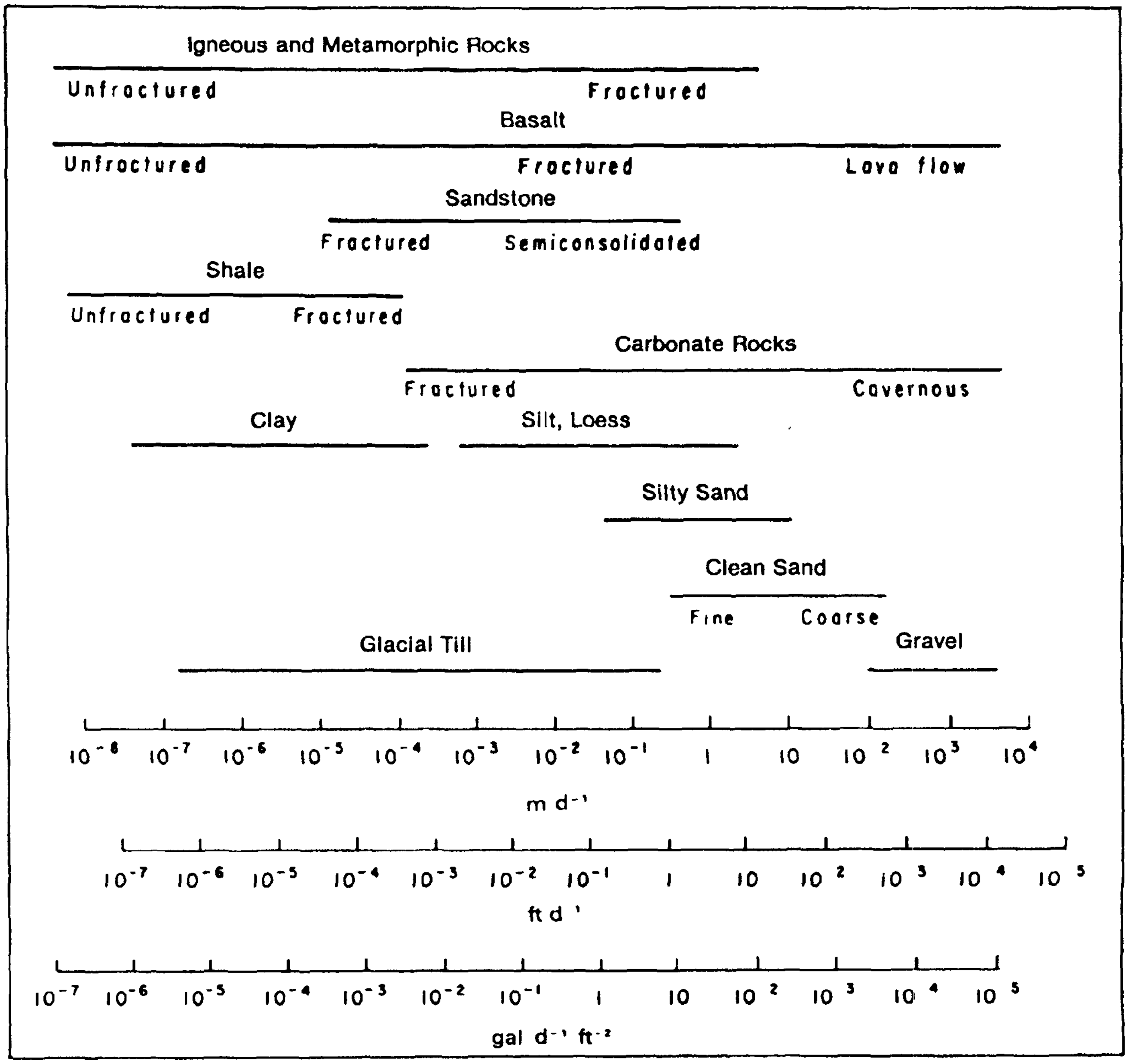

Figure 4-11. General Range in Hydraulic Conductivity for Various Rock Types

elevation. In the case of a confined aquifer, however, the water may have the potential to rise to a certain elevation, but it cannot actually do so until the confining unit is perforated by a well. Therefore, a potentiometric surface map of a confined aquifer represents an imaginary surface.

A potentiometric surface map can be developed into a flow net by constructing flow lines that intersect the equipotential lines at right angles. Flow lines are imaginary paths that would be followed by particles of water as they move through the aquifer. Although there is an infinite number of both equipotential and flow lines, the former are constructed with uniform differences in elevation between them and the latter so that they form, in combination with equipotential lines, a series of squares. A carefully prepared flow net in conjunction with Darcy's Law (discussed below) can be used to estimate the quantity of water flowing through an area.

A plan view flow net of an unconfined aquifer is shown in Figure 4-16. Notice that all of the water-table contours point upstream, and that the flow lines originate in the central part of the interstream divide (recharge area) and terminate at the streams (discharge line). A vertical

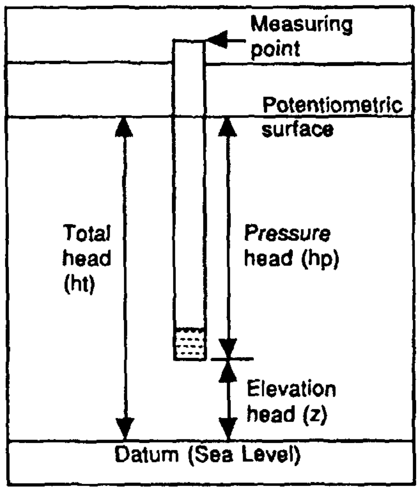

Figure 4-12. Relationship Between Total Head, Pressure Head, and Elevation Head

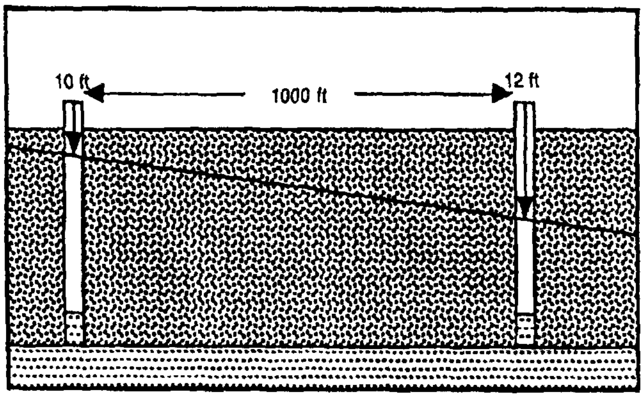

Figure 4-13. The Hydraulic Gradient Is Defined by the Decline in Water Level in Wells a Defined Distance Apart

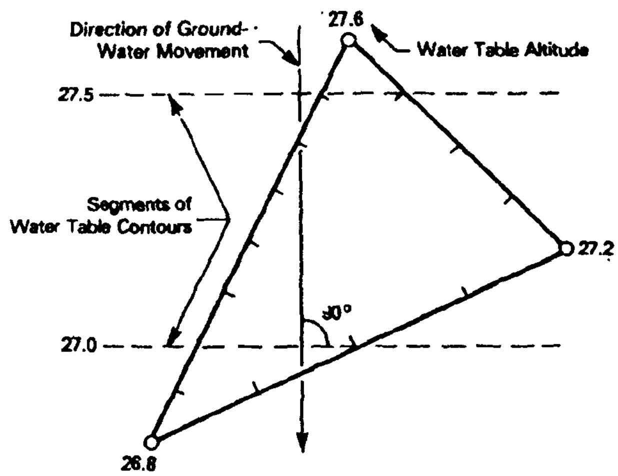

Figure 4-14. The Generalized Direction of Ground-Water Movement Can Be Determined by Means of the Water Level in Three Wells of Similar Depth (From Heath and Trainer, 1981)

flow net, representing the line A-A' in Figure 4-16, is shown in Figure 4-17. In this case, the curved flow lines illustrate that the ground water is moving in the same direction but not in the same manner as implied from the plan view.

A flow net that represents a different hydrologic situation is shown in Figure 4-18. In this case, the streams are gaining in the upper part of the map, while below their confluence the water-table contours begin to point downstream. This indicates that the water table is below the channel, the stream is losing water to the subsurface, and the flow lines are diverging from the line source of recharge. A vertical flow net is shown in Figure 4-19.

Ground water flows not only through aquifers, but across confining units as well. Owing to the great differences in hydraulic conductivity between aquifers and confining units, most of the flow occurs through aquifers where the head loss per unit of distance is far less than in a confining unit. As a result, flow lines tend to parallel aquifer boundaries; they are less dense and trend nearly perpendicular through confining units (fig. 4-20). Consequently, lateral flow in units of low hydraulic conductivity is small compared to aquifers, but vertical leakage through them can be significant. Where an aquifer flow line intersects a confining unit the flow line is refracted to produce the shortest path. The degree of refraction is proportional to the differences in hydraulic conductivity.

Calculating Ground-Water Flow

Darcy's Law, expressed in many different forms, is used to calculate the quantity of underflow or vertical leakage. One means of expressing it is:

$$Q = KIA \quad (11)$$

where:

- Q = quantity of flow, in gpd
- A = cross-sectional area through which the flow occurs, in ft^2
- K = hydraulic conductivity, in gpd/ft^2
- I = hydraulic gradient, in ft/ft

The flow rate is directly proportional to the gradient and therefore the flow is laminar, which means the water will follow distinct flow lines rather than mix with other flow lines. Where laminar flow does not occur, as

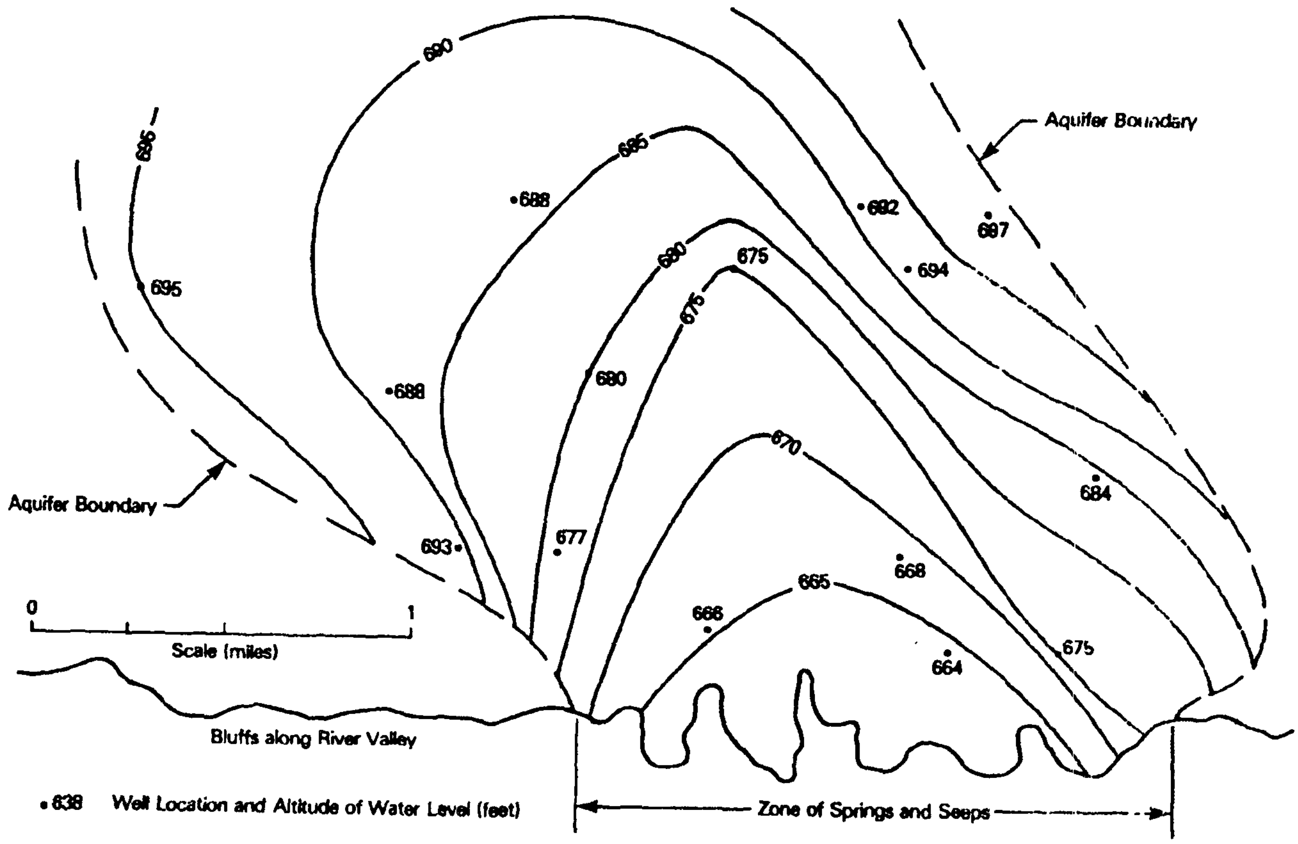

Figure 4-15. A Potentiometric Surface Map Representing the Hydraulic Gradient in an Aquifer that Crops Out Along the Bluffs of a River Valley

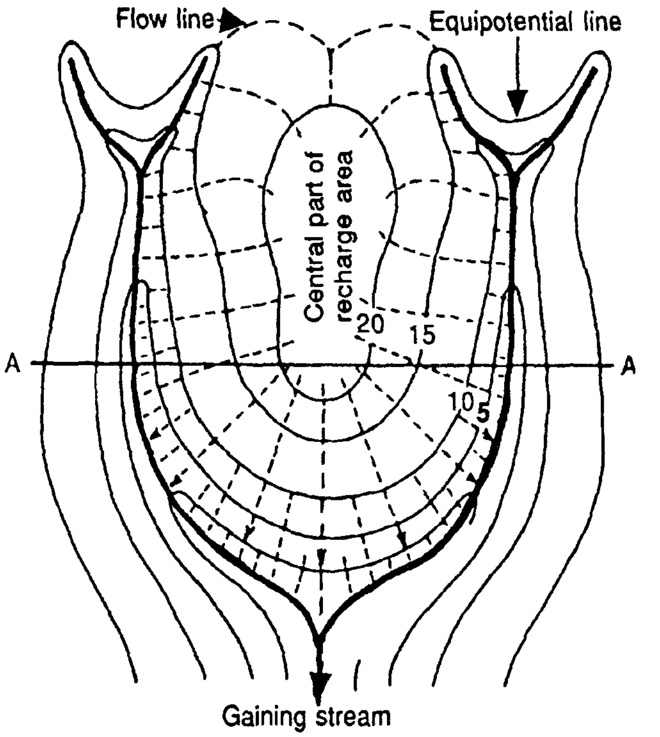

Figure 4-16. Plan View Flow Net of an Unconfined Aquifer (Modified from Heath, 1983)

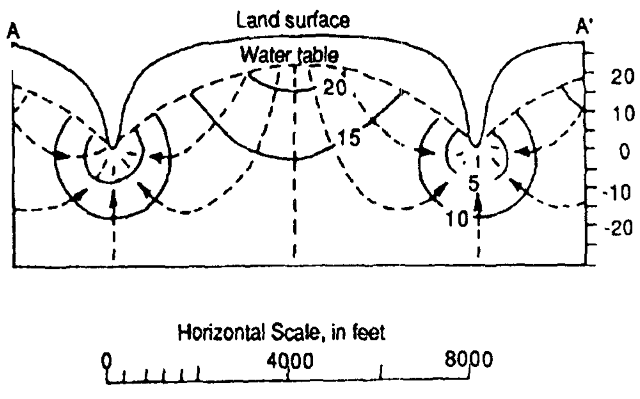

Figure 4-17. Vertical Flow Net of an Unconfined Aquifer (Modified from Heath, 1983)

in the case of unusually high velocity, which might be found in fractures, solution openings, or adjacent to some pumping wells, the flow is turbulent.

As an example of Darcy's Law, notice in Figure 4-21A that a certain quantity (Q) of fluid enters the sand-filled tube, with a cross section of A, and the same amount exits. The water level declines along the length of the flow path (L) and the head is higher in the manometer

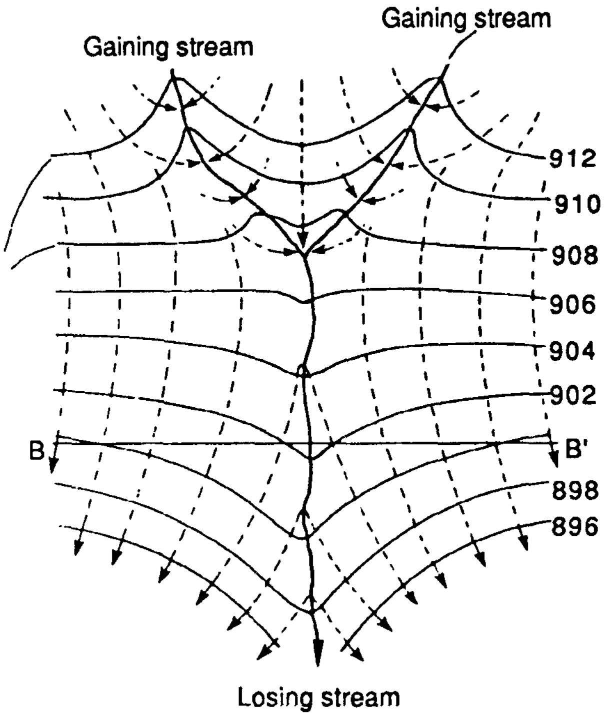

Figure 4-18. Plan View Flow Net of an Unconfined Aquifer Where Streams Change from Gaining to Losing (Modified from Heath, 1983)

at the beginning of the flow path than it is at the other end. The difference in head (H) along the flow path (L) is the hydraulic gradient (H/L or I). The head loss reflects the energy required to move the fluid this distance. If Q and A remain constant but K is increased, then the head loss decreases. It is important to keep in mind the fact that the head loss occurs in the direction of flow.

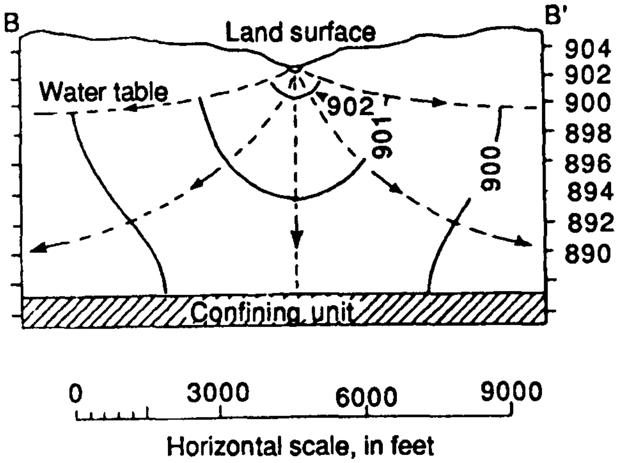

Figure 4-19. Vertical Flow Net of an Unconfined Aquifer with a Losing Stream (Modified from Heath, 1983)

In Figure 4-21B, the flow tube has been inverted and the water is flowing from bottom to top or top to bottom. Q, K, A, and I all remain the same. This illustrates an important concept when the manometers are considered as wells. Notice that the deeper well has a head that is higher than the shallow well when the water is moving upward, while the opposite is the case when the flow is downward.

Where nearby wells of different depths and water levels occur in the field, as shown in Figure 4-21C, it clearly indicates the existence of recharge and discharge areas. In recharge areas, shallow wells have a higher head than deeper wells; the difference indicates the energy required to vertically move the water the distance

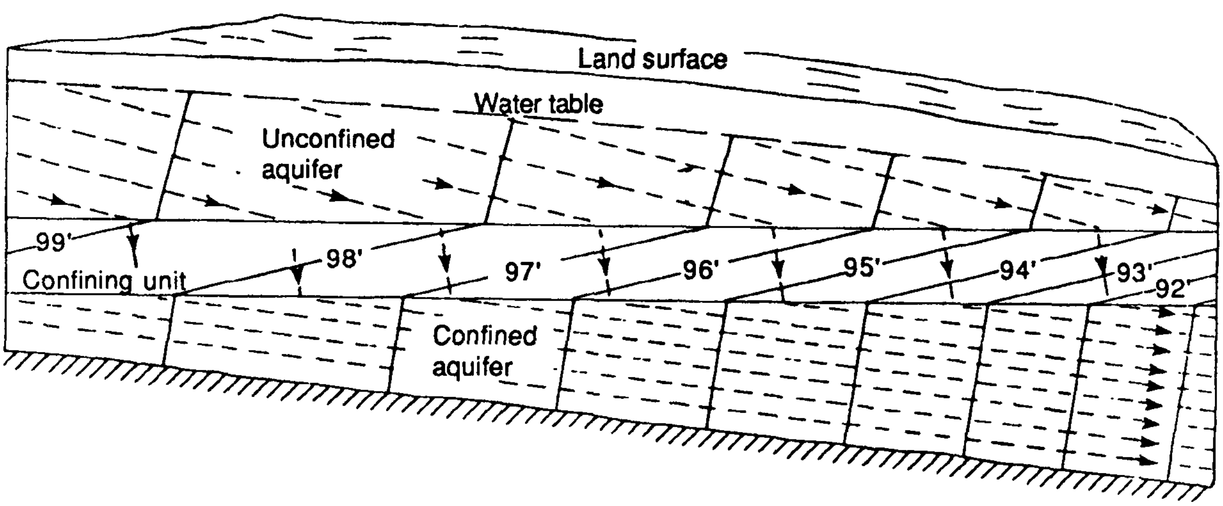

Figure 4-20. Flow Lines in Aquifers Tend to Parallel Boundaries but in Confining Units They are Nearly Perpendicular to Boundaries (Modified from Heath, 1983)

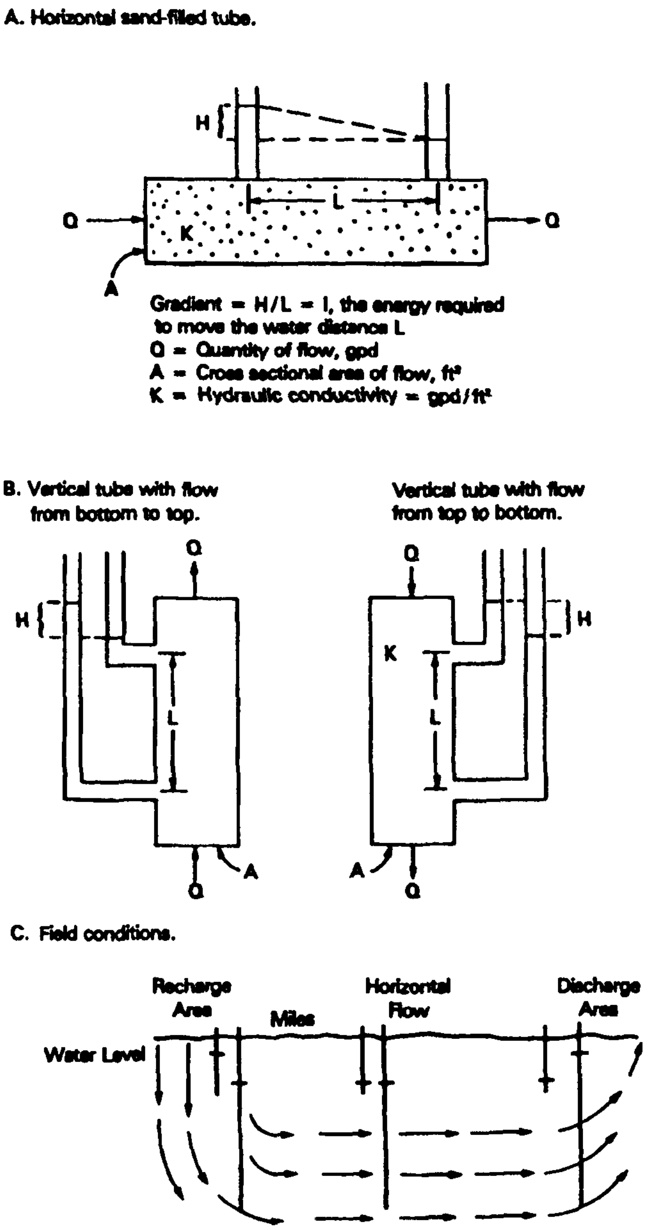

Figure 4-21. Graphical Explanation of Darcy's Law. Notice That the Flow in a Tube can be Horizontal or Vertical in the Direction of Decreasing Head

between the screens of the two wells. Where the flow is horizontal, there should be no difference in head. In discharge areas, the deeper well will have the higher head. Waste disposal in recharge areas might lead to the vertical migration of leachate to deeper aquifers and, from this perspective, disposal sites should be located in discharge areas.

An example of the use of Darcy's Law, consider a sand aquifer, about 30 feet thick, that lies within a mile wide flood plain of a river. The aquifer is covered by a confining unit of glacial till, the bottom of which is about 45 feet below land surface. The difference in water level in two wells a mile apart is 10 feet. The hydraulic conductivity of the sand is 500 gpd/ft^2. The quantity of underflow passing through a cross-section of the river valley is:

$$Q = KIA$$
$$= 500\ \text{gpd/ft}^2 * (10\ \text{ft}/5280\ \text{ft}) * (5280\ \text{ft}*30\ \text{ft})$$
$$= 150{,}000\ \text{gpd} \quad (12)$$

The quantity of flow from one aquifer to another through a confining unit can be calculated by a slightly modified form of Darcy's Law.

$$Q_L = (K'/m')AH \quad (13)$$

where

Q_L = quantity of leakage, in gpd
K' = vertical hydraulic conductivity of the confining unit, gpd/ft^2
m' = thickness of the confining unit, ft
A = cross-sectional area through which leakage is occurring, ft^2
H = difference in head between the two wells tapping the upper and lower aquifers, ft

As illustrated in Figure 4-22, assume two aquifers are separated by a layer of silt. The silty confining unit is 10 feet thick and has a vertical hydraulic conductivity of 2 gpd/ft^2. The difference in water level in wells tapping the upper and lower aquifers is 2 feet. Let us also assume that these hydrogeologic conditions exist in an area that is a mile long and 2000 feet wide. The daily quantity of leakage that occurs within this area from the deep aquifer to the shallow aquifer is

$$Q = (2\ \text{gpd/ft}^2/10\ \text{ft}) * (5{,}280\text{ft}*2{,}000\ \text{ft}) * 2\ \text{ft} \quad (14)$$
$$= 4{,}224{,}000\ \text{gpd}$$

This calculation clearly shows that the quantity of leakage, either upward or downward, can be immense even if the hydraulic conductivity of the aquitard is small.

Interstitial Velocity

The interstitial velocity of ground water is of particular importance in contamination studies. It can be estimated by the following equation.

$$v = KI/7.48n \quad (15)$$

where:

v = average velocity, in ft per day
n = effective porosity

Other terms are as previously defined.

As an example, assume there is a spill that consists of a conservative substance, such as chloride. The

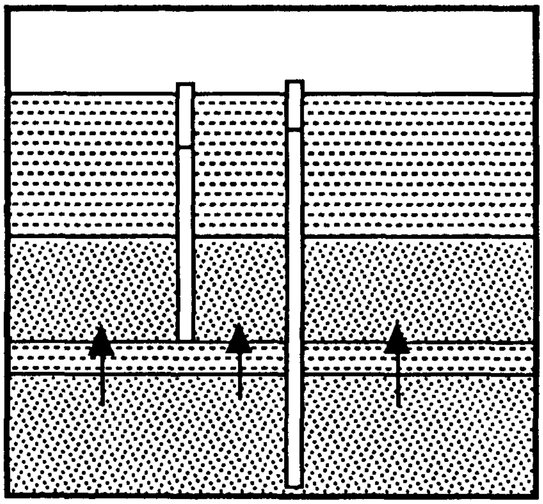

Figure 4-22. Example of Interaquifer Leakage

liquid waste infiltrates through the unsaturated zone and quickly reaches a water-table aquifer that consists of sand and gravel with a hydraulic conductivity of 2,000 gpd/ft^2 and an effective porosity of 0.20. The water level in a well at the spill lies at an altitude of 1,525 feet and at a well a mile directly downgradient it is at 1,515 feet (fig. 4-23). What is the velocity of the water and contaminant and how long will it be before the second well is contaminated by chloride?

$$v = (2{,}000\ \text{gpd/ft}^2 * (10\ \text{ft}/5{,}280\ \text{ft}))/7.48 * .20$$
$$= 2.5\ \text{ft/day} \quad (16)$$

$$\text{Time} = 5{,}280\ \text{ft}/2.5\ \text{ft/day}$$
$$= 2{,}112\ \text{days or } 5.8\ \text{years}$$

This velocity value is crude at best and can only be used as an estimate. Hydrodynamic dispersion, for example, is not considered in the equation. This phenomenon causes particles of water to spread transverse to the major direction of flow and move downgradient at a rate faster than expected. It is caused by an intermingling of streamlines due to differences in interstitial velocity brought about by the irregular pore space and interconnections.

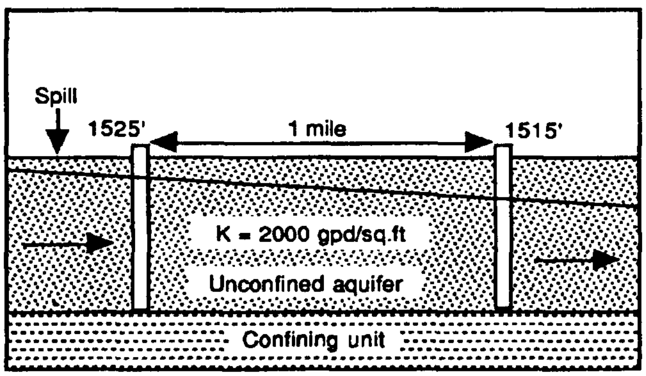

Figure 4-23. Using Ground-Water Velocity Calculations, It Would Require Nearly 6 Years for the Center of Mass of the Spill to Reach the Downgradient Well

Furthermore, most chemical species are retarded in their movement by reactions with the geologic framework, particularly with certain clays, soil-organic matter, and selected hydroxides. Only conservative substances, such as the chloride ion, will move unaffected by retardation (see Chapter 5).

In addition, it is not only the water below the water table that is moving, but also fluids within the capillary fringe. Here the velocity diminishes rapidly upward from the water table. Movement in the capillary fringe is important where the contaminant is gasoline or other substances less dense than water.

Transmissivity and Storativity

Hydrogeologists commonly use the term transmissivity (T) to describe an aquifer's capacity to transmit water. Transmissivity is equal to the product of the aquifer thickness (m) and hydraulic conductivity (K) and it is described in units of gpd/ft (gallons per day per foot of aquifer thickness).

$$T = Km \quad (17)$$

Another important term is storativity (S), which describes the quantity of water that an aquifer will release from or take into storage per unit surface area of the aquifer per unit change in head. In unconfined aquifers the storativity is, for all practical purposes, equal to the specific yield and, therefore, it should range between 0.1 and 0.3. The storativity of confined aquifers is substantially smaller because the water that is released from storage when the head declines comes from the expansion of water and compaction of the aquifer, both of which are exceedingly small. For confined aquifers the storativity generally ranges between 0.0001 and 0.00001, and for leaky confined aquifers it is in the range of 0.001. On method to estimate storativity for confined aquifers is to multiply the aquifer thickness by 0.000001 The small storativity for confined aquifers means that to obtain a sufficient supply from a well there must be a large pressure change throughout a wide area. This is not the case with unconfined aquifers because the water derived is not related to expansion and compression but comes instead from gravity drainage and dewatering of the aquifer.

Hydrogeologists have found it necessary to use transmissivity and storativity coefficients to calculate the response of an aquifer to stresses and to predict future water-level trends. These terms also are required as input for most flow and transport computer models.

Water-Level Fluctuations

Ground-water levels fluctuate throughout the year in response to natural changes in recharge and discharge, to changes in pressure, and to artificial stresses, such as pumping. Fluctuations brought about by changes in pressure are limited to confined aquifers. Most of these changes, which are short term, are caused by loading, such as a passing train compressing the aquifer or an increase in discharge from an overlying stream. Other water-level fluctuations are related to changes in barometric pressure, tides, earthtides, and earthquakes. None of these fluctuations reflect a change in the volume of water in storage.

An examination of the rise and fall of the water level in a well tapping flood plain deposits may lead to erroneous conclusions. If the aquifer is unconfined, a water-level rise implies ground-water recharge. On the other hand, a similar rise in a confined aquifer may be the result of loading brought about by the additional weight as the discharge of the stream increases. Generally ground-water recharge would lag behind an increase in stream discharge, while pressure loading would be concomitant (fig. 4-24).

Fluctuations that involve changes in storage are generally more long lived (fig. 4-25). Most ground-water recharge takes place during the spring and fall. Following these periods, which are a month or two long,

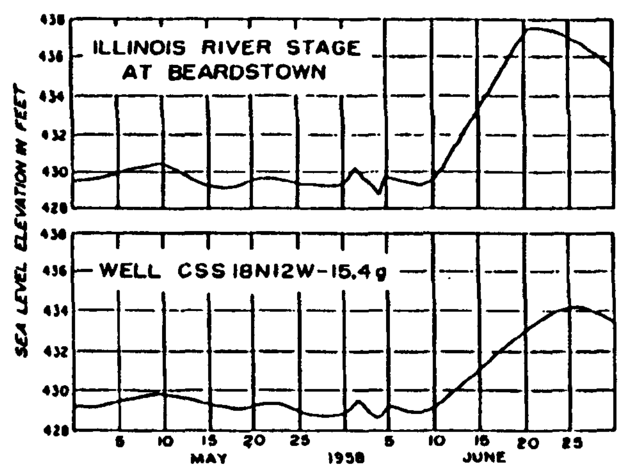

Figure 4-24. Effect of Increasing River Stage on the Water Level in a Well Tapping a Confined Aquifer (From Walton, 1970)

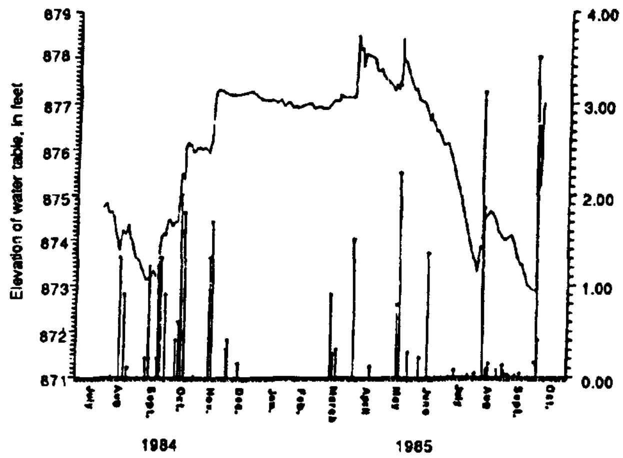

Figure 4-25. Relationship Between Precipitation and Water Level in a Well Tapping a Fine-Grained, Unconfined Aquifer

the water level declines in response to natural discharge, which is largely to streams. Although the major period of recharge occurs in the spring, minor events can happen any time there is a rain.

The volume of water added or removed from ground-water storage can be estimated by the following equation:

$$V_w = V_r S \quad (17)$$

where

V_w = the volume of water, in cubic feet

V_r = the volume of rock through which the water level has changed

S = storativity

For example, following a rain the water table rises a half a foot throughout an area of 10,000 square feet. If the aquifer has a storativity of 0 .2, then 1000 cubic feet or or nearly 7,500 gallons of water were added to storage. In this regard, Figure 4-25 shows an interesting relationship. Notice in April 1985 that the water table rose about 1.3 feet following 1.5 inches of rain, but in May the water table rose only about 1 foot after two storms provided more than twice the amount of rain (3.1 inches). This phenomenon suggests that the storativity changed, but actually the effect is related to soil moisture. When the unsaturated zone has a high soil-moisture content (April), the fillable porosity is less than it is when the moisture content is low (May); therefore, the greater the moisture content, the higher the water table rise.

Evapotranspiration effects on a surficial or shallow aquifer are both seasonal and daily. Trees, each serving as a minute pump, remove water from the capillary fringe or even from beneath the water table during hours of daylight in the growing season (fig. 4-26). In turn, this results in a diurnal fluctuation in the water table and it might influence streamflow as well.

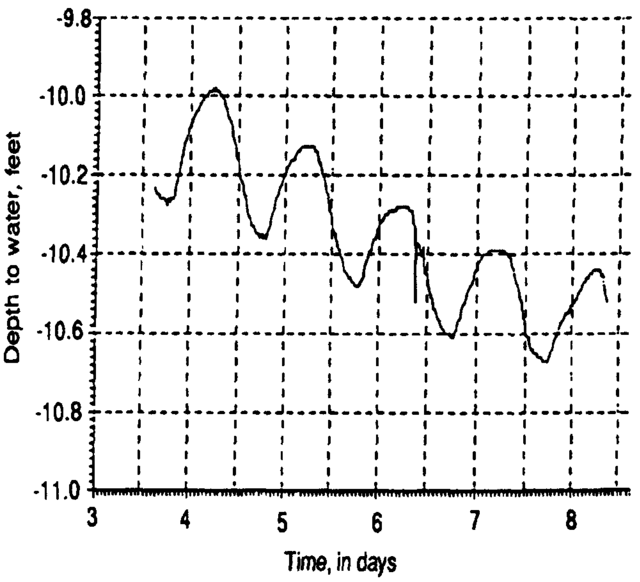

Figure 4-26. Hydrograph of a Well, 14 Feet Deep, that Is Influenced by Transpiration

Cone of Depression

When a well is pumped, the water level in its vicinity declines to provide a gradient to drive water toward the discharge point. The gradient becomes steeper as the well is approached because the flow is converging from all direction, and the area through which the flow is occurring gets smaller. This results in a cone of depression around the well. Relatively speaking, the cone of depression around a well tapping an unconfined aquifer is small if compared to that around a well in a confined system. The former may be a few tens to a few hundred of feet in diameter, while the latter may extend outward for miles (fig. 4-27). By means of aquifer tests, which analyze the cone of depression, coefficients of transmissivity and storativity, as well as other hydraulic parameters can be determined.

Cones of depression from several pumping wells may overlap and, since their drawdown effects are additive, the water-level decline throughout the area of influence is greater than from a single cone (fig. 4-28). In ground-water studies, and particularly contamination problems, evaluation of the cone or cones of depression can be critical because they represent an increase in the hydraulic gradient, which in turn controls ground-water velocity and direction of flow. In fact, properly spaced and pumped wells provide a mechanism to control the migration of leachate plumes. Discharging and recharging well schemes are commonly used in attempts to restore contaminated aquifers (see Chapter 7).

Specific Capacity

The decline of the water level in a pumping well, or any well for that matter, is called the drawdown and the pre-

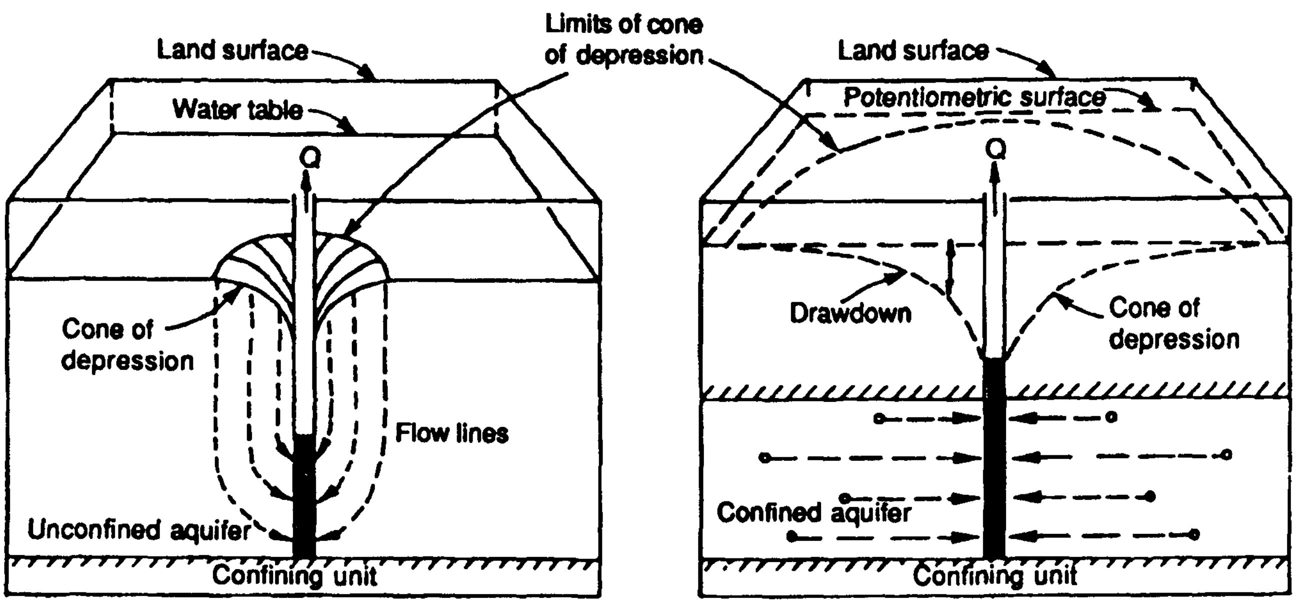

Figure 4-27. Cones of Depression In Unconfined and Confined Aquifers (From Heath, 1983)

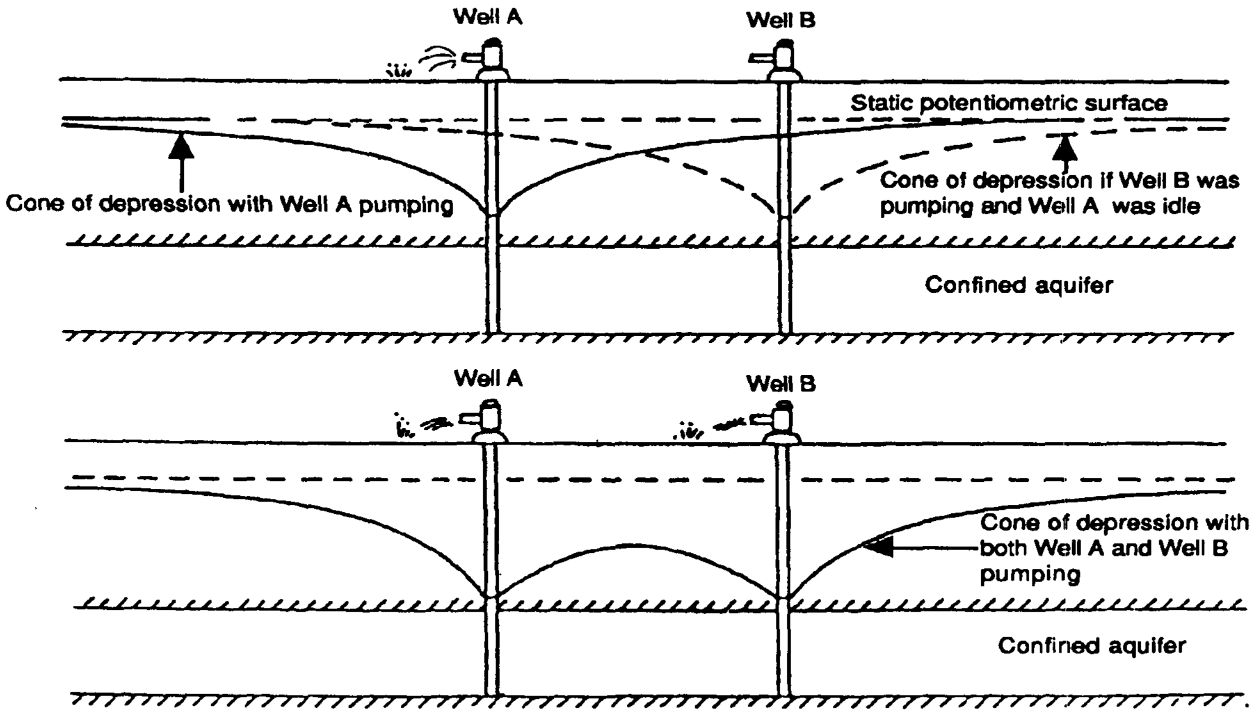

Figure 4-28. Overlapping Cones of Depression Result In More Drawdown Than Would Be the Case for a Single Well (Modified from Heath, 1983)

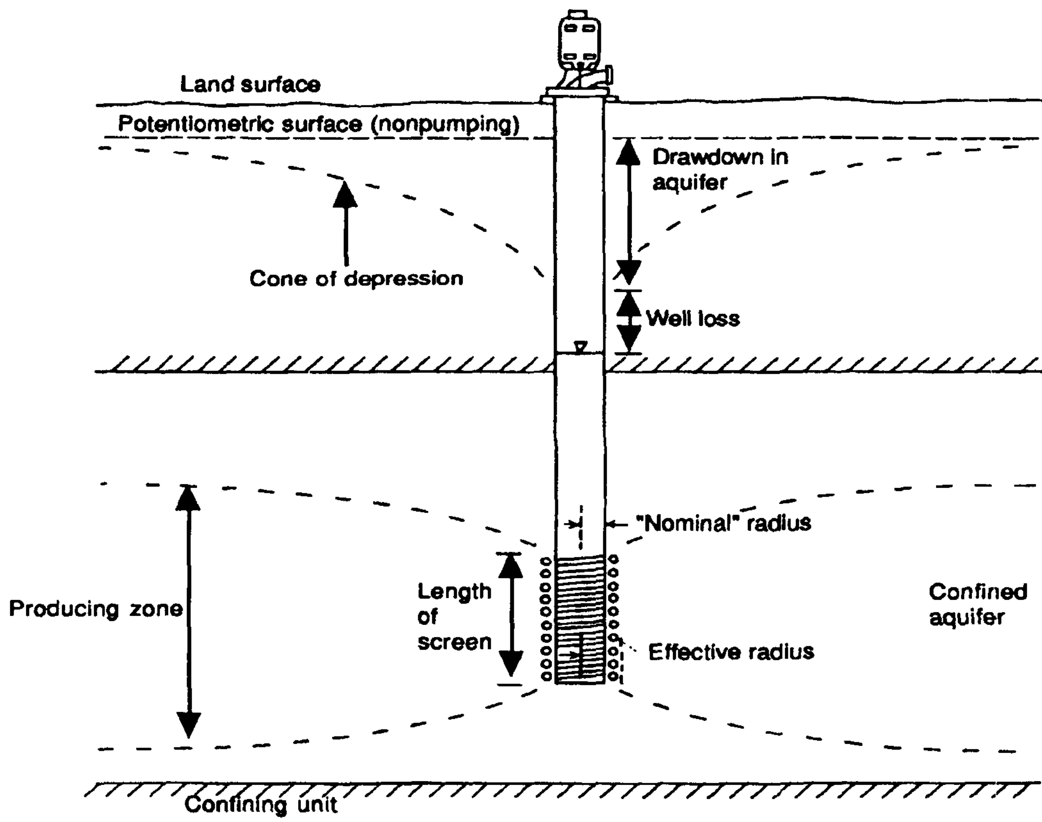

Figure 4-29. Values of Transmissivity Based on Specific Capacity Commonly are Too Low Because of Well Construction Details that Increase Well Loss (Modified from Heath, 1983)

pumping level is the static water level (fig. 4-29). The discharge rate of the well divided by the difference between the static and the pumping level is the specific capacity. The specific capacity indicates how much water the well will produce per foot of drawdown.

$$\text{Specific capacity} = Q/s \quad (18)$$

where

Q = the discharge rate, in gpm
s = the drawdown, in ft

If a well produces 100 gpm and the drawdown is 8 feet, the well will produce 12.5 gallons per minute for each foot of available drawdown. One can rather crudely estimate transmissivity of confined aquifers by multiplying specific capacity by 2,000 and by 1,550 in the case of unconfined systems.

The material presented in this chapter is both brief and generalized, but it should provide sufficient information and general principles to allow one to develop some understanding of hydrogeology. Greater detail can be obtained from the literature mentioned in the references.

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Chapter 5

GROUND-WATER CONTAMINATION

Introduction

For millennia, humans have disposed of waste products in a variety of ways. The method might reflect convenience, expedience, expense, or best available technology, but in many instances, leachates from these wastes have come back to haunt later generations. Ground-water contamination may lead to problems of inconvenience, such as taste, odor, color, hardness, or foaming, but the problems are far more serious when pathogenic organisms, flammable or explosive substances, or toxic chemicals and their by-products are present.

Presently, most regulatory agencies are concerned with ground-water contamination cases that involve organic compounds, and this is the result of the rapid growth of the synthetic organic chemical industry in the United States during the last 50 years. At least 63,000 synthetic organic chemicals are in common industrial and commercial use in the United States, and the number increases by 500 to 1,000 each year. Furthermore, health effects brought about by long term, low level exposures are not well known.

More than 200 chemical constituents in ground water have been documented, including approximately 175 organic compounds and more than 50 inorganic chemicals and radionuclides (OTA, 1984). The sources of these chemicals are both natural and human-induced. In a survey conducted by the U.S. EPA, volatile organic compounds (VOCs) were detected in 466 randomly selected public ground-water supply systems. One or more VOCs were detected in 16.8 percent of small systems and 28.0 percent of the larger systems sampled. Those occurring most often were trichloroethylene (TCE) and tetrachloroethylene (PCE).

In the lesser developed countries, contamination of water supplies by organic compounds is of minor concern, or of no concern at all. In such places the major health problems are the result of poor sanitary conditions and illness brought about by pathogenic organisms. In Mexico, for example, 10 percent of the the individuals who perish each year die from diarrhea, which is caused by the ingestion of contaminated food, water, and air. The primary health-related goal of water treatment is disinfection, and the emphasis over the past several years on synthetic organic compounds in drinking water in the United States has overshadowed this goal.

Individual contaminated sites generally are not large, but once degraded, ground water may remain in an unusable or even hazardous condition for decades or even centuries (Pettyjohn, 1979). The typically low velocity of ground water prevents a great deal of mixing and dilution; consequently, a contaminant plume may maintain a high concentration as it slowly moves from points of recharge to zones of discharge.

Sources of Ground-Water Contamination

As water moves through the hydrologic cycle, its quality changes in response to differences in the environments through which it passes. The changes may be either natural or human-influenced; in some cases they can be controlled, in other cases they cannot, but in most instances they can be managed in order to limit adverse water-quality changes.

The physical, chemical, and biological quality of water may range within wide limits. In fact, it is often impossible or at least difficult to distinguish the origin (human-made or natural) of many water-quality problems. Natural quality reflects the types and amounts of soluble and insoluble substances with which the water has come in contact. Surface water generally contains less dissolved solids than ground water, although at certain times where ground-water runoff is the major source of streamflow, the quality of both surface water and ground water is similar. During periods of surface runoff, streams may contain large quantities of suspended materials and, under some circumstances, a large amount of dissolved solids. Most commonly, however, during high rates of flow streams have a low dissolved-mineral concentration.

Although the chemical quality of water in surficial or shallow aquifers may range within fairly broad limits from one time to the next, deeper ground water is characterized by nearly constant chemical and physical properties, at least on a local scale where the aquifer is unstressed by pumping. As a general rule, dissolved solids increase with depth and with the time and distance the water has traveled in the ground. A few uncommon water-quality situations exist throughout the country, reflecting peculiar geologic and hydrologic conditions. These include, among others, thermal areas and regions characterized by high concentrations of certain elements, some of which may be health hazards.

For centuries humans have been disposing of waste products by burning, placing them in streams, storing them on the ground, or putting them in the ground. Human-induced influences on surface-water quality reflect not only waste discharge directly into a stream, but also include contaminated surface runoff. Another major influence on surface-water quality is related to the discharge of ground water into a stream. If the adjacent ground water is contaminated, stream quality tends to deteriorate. Fortunately in the latter case because of dilution, the effect in the stream generally will not be as severe as it is in the ground.

The quality of ground water most commonly is affected by waste disposal and land use. One major source of contamination is the storage of waste materials in excavations, such as pits or mines. Water-soluble substances that are dumped, spilled, spread, or stored on the land surface eventually may infiltrate. Ground water also can become contaminated by the disposal of fluids through wells and, in limestone terrains, through sinkholes directly into aquifers. Likewise, infiltration of contaminated surface water has caused ground-water contamination in several places. Irrigation tends to increase the mineral content of both surface and ground water. The degree of severity in cases such as these is related to the hydrologic properties of the aquifers, the type and amount of waste, disposal techniques, and climate.

Another cause of ground-water quality deterioration is pumping, which may precipitate the migration of more mineralized water from surrounding strata to the well. In coastal areas pumping has caused seawater to invade fresh-water aquifers. In parts of coastal west Florida, wild-flowing, abandoned artesian wells have salted, and consequently ruined, large areas of formerly fresh or slightly brackish aquifers.

Ground-Water Quality Problems that Originate on the Land Surface

1. Infiltration of contaminated surface water
2. Land disposal of solid and liquid waste materials
3. Stockpiles, tailings, and spoil
4. Dumps
5. Disposal of sewage and water-treatment plant sludge
6. Salt spreading on roads
7. Animal feedlots
8. Fertilizers and pesticides
9. Accidental spills
10. Particulate matter from airborne sources

Ground-Water Quality Problems that Originate Above the Water Table

1. Septic tanks, cesspools, and privies
2. Surface impoundments
3. Landfills
4. Waste disposal in excavations
5. Leakage from underground storage tanks
6. Leakage from underground pipelines
7. Artificial recharge
8. Sumps and dry wells
9. Graveyards

Ground-Water Quality Problems that Originate Below the Water Table

1. Waste disposal in wet excavations
2. Agricultural drainage wells and canals
3. Well disposal of wastes
4. Underground storage
5. Secondary recovery
6. Mines
7. Exploratory wells and test holes
8. Abandoned wells
9. Water supply wells
10. Ground-water development

Table 5-1. Sources of Ground-Water Quality Deterioration

Table 5-1 shows that ground-water quality problems are most commonly related to: (l) water-soluble products that are stored or spread on the land surface, (2) substances that are deposited or stored in the ground above the water table, and (3) material that is stored, disposed of, or extracted from below the water table. Many of the contamination problems related to these activities are highly complex, and some are not well understood.

Ground-Water Quality Problems that Originate on the Land Surface

Infiltration of Contaminated Surface Water. The yield of many wells tapping streamside aquifers is sustained by

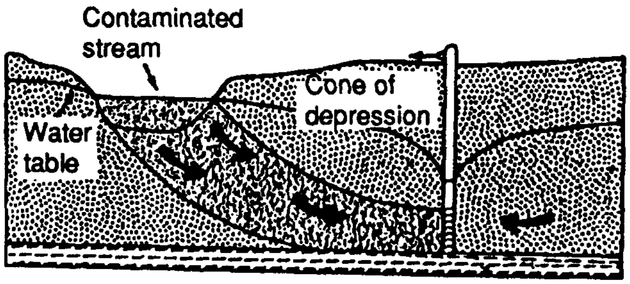

Figure 5-1. Induced Infiltration from a Contaminated Stream Will Degrade Ground-Water Quality

infiltration of surface water (fig. 5-1). In fact, more than half of the well yield may be derived directly by induced recharge from an adjacent surface-water source, which may be contaminated. As the induced water migrates through the subsurface, a few substances are diluted or removed, particularly where the water flows through filtering materials, such as sand and gravel, or organic matter. Filtration is not likely to occur if the water flows through large openings, such as those in some carbonate aquifers. Chloride, nitrate, and several organic compounds, are highly mobile, move freely with the water, and are not removed by filtration.

Examples of the degradation of ground-water supplies by induced infiltration of contaminated surface water are both numerous and widespread. In the greatest number of cases, the contamination originated from the disposal of municipal or industrial waste directly into a stream, which was then induced by pumping into adjacent aquifers. In hydrologic situations such as these, months or even years may be required for the contaminant to reach a well, but once there, all of the intervening area may be completely degraded.

Land Disposal of Solid and Liquid Waste Materials. One cause of ground-water contamination is the disposal of waste materials directly onto the land surface. Examples include manure, sludges, garbage, and industrial wastes. The waste may occur as individual mounds or it may be spread over the land. If the waste material contains soluble substances, they may infiltrate. Similar problems occur in the vicinity of various types of stockpiles.

Stockpiles, Tailings, and Spoil. Perhaps the prime example of ground-water contamination caused by stockpiles is unprotected storage of de-icing salt (sodium and calcium chloride), commonly mixed with sand, at highway maintenance lots. The salt readily dissolves to either infiltrate or run off. An average sized stockpile may contain 150 to 250 tons of salt, with anticaking additives, such as ferric ferrocyanide and sodium ferrocyanide, and perhaps phosphate and chromate to reduce corrosivity (Williams, 1984).

Other stockpiles include coal, metallic ores, phosphates, and gypsum. Both coal and metal sulfide ores, when weathered, may cause acid drainage, and the resulting low pH water may dissolve additional constituents from the ore or from other earth materials that it contacts.

Tailings, which consist of ore of a grade too low for further treatment, also may generate acid waters. They are commonly associated with ponds used for the disposal of mining wastes from cleaning and ore concentration. As a general rule, tailings ponds are unlined and, when eventually filled with slurry, are abandoned; they may serve as sources of acid, metals, dissolved solids, and radioactivity.

The debris or waste material produced during mining is called spoil. For over a century, iron-sulfide-rich spoil has served as a major source of acid-mine drainage in the eastern coal fields and at metal sulfide mines throughout the country.

Dumps. During the past two decades, investigators have taken a serious look at the environmental effects of dumps. As rainwater infiltrates through trash in a dump, it accumulates an ample assortment of chemical and biological substances. The resulting fluid, or leachate, may be highly mineralized, and as it infiltrates, some of the substances it contains may not be removed or degraded.

Disposal of Sewage and Water Treatment Plant Sludge. Sludge is the residue of chemical, biological, and physical treatment of municipal and industrial wastes. They include lime-rich material from water treatment plants, as well as sewage sludge from wastewater treatment plants. Sludges typically contain partly decomposed organic matter, inorganic salts, heavy metals, bacteria, and perhaps viruses. Nitrogen in municipal sludge may vary from 1 to 7 percent. Land application of wastewater and sewage sludge is an alternative to conventional treatment and disposal, and is in common usage by the canning and vegetable industry, petroleum refining, pulp and paper, and the power industry. Contamination results from the infiltration of partly treated wastewaters that have not undergone sufficient attenuation.

Infiltration from wastewater stabilization ponds also can cause ground-water contamination. Ponds of this type primarily are used for settlement of suspended solids and biological treatment of primary and secondary effluent.

Salt Spreading on Roads. Especially since the construction of the interstate highway system, water contamination due to wintertime road salting has become an increasing problem. From a quality viewpoint, the salting may bring about deterioration of streams due to surface runoff, and infiltration causes ground-water contamination. Numerous instances of contamination have been reported in the New England states and Michigan.

On the outskirts of Muskegon, MI, which lies on a sandy plain adjacent to Lake Michigan, a class action suit was filed against a county wastewater treatment operation that uses large upground lagoons, alleging contamination of several domestic wells. Evidence presented at a pretrial hearing clearly showed, however, that a few of the domestic wells had been contaminated from time to time, but the source was de-icing salt spread on high crowned roads that were bordered by wide, deep ditches cut into the sand of an unconfined aquifer. All of the domestic wells were adjacent to the road ditches and, when pumping, induced salty water to the well.

Accidental Spills. A large volume of toxic materials are transported throughout the country by truck, rail, and aircraft, transferred at handling facilities, and stored in tanks; accidental spills of these materials are commonplace. It has been estimated that about 16,000 spills, ranging from a few to several million gallons, occur each year, and these include hydrocarbons, paint products, flammable materials, acids and anhydrous ammonia, among many others (National Academy of Sciences, 1983). Virtually no methods are available to quickly and adequately clean up an accidental spill or those caused by explosions or fires. Furthermore, immediately following an accident, the usual procedure is to spray the area with water. The resulting fluid may either flow into a stream or infiltrate. In a few cases, the fluids have been impounded by dikes, causing even more infiltration.

Fertilizers and Pesticides. Increasing amounts of both fertilizers and pesticides are being used in the United States each year. Reportedly, there are more than 32,000 different compounds consisting of an excess of 1,800 active ingredients used in agricultural applications (Houzim and others, 1986). Many are highly toxic and, in countless cases, quite mobile in the subsurface. Numerous compounds, however, become quickly attached to fine-grained sediment, such as organic matter and clay and silt particles. A part of this attached material is removed by erosion and surface runoff. In many heavily fertilized areas, the infiltration of nitrate, a decomposition product of ammonia fertilizer, has adversely affected ground water. The consumption of nitrate-rich water leads to a disease in infants known as "blue babies" (methemoglobinemia).

In some irrigated regions, automatic fertilizer feeders are attached to irrigation sprinkler systems. When the pump is shut off, water flows back through the pipe into the well bore, creating a partial vacuum that may cause fertilizer to flow from the feeder into the well. It is possible that some individuals even dump fertilizers (and perhaps pesticides) directly into the well to be picked up by the pump and distributed to the sprinkler system.

Aurelius (1989) described an investigation in Texas where 188 wells were sampled for nitrate and pesticides in 10 counties where aquifer vulnerability studies and field characteristics indicated the potential for ground-water contamination from the normal use of agricultural chemicals. Nine pesticides (2,4,5-T, 2,4-DB, metolachlor, dicamba, atrazine, prometon, bromacil, picloram, and triclopyr) were found present in 10 wells, nine of which were used for domestic supply. Also, 182 wells were tested for nitrate and of these, 101 contained more than the recommended limit. Of the high nitrate wells, 87 percent were used for household purposes. In addition, 28 wells contained arsenic at or above the limit of 0.05 mg/L, and 23 of these were domestic wells.

Animal Feedlots. Feedlots, used for cattle, hogs, sheep, and poultry, cover relatively small areas but provide a huge volume of wastes. These wastes and seepage from lagoons have contaminated both surface and ground water with large concentrations of nitrate, phosphate, chloride, and bacteria.

Particulate Matter from Airborne Sources. A relatively minor source of ground-water contamination is caused by acid rain and the fallout of particulate matter originating from smoke, flue dust, or aerosols, and from automobile emissions. Some of the particulate matter is water-soluble and toxic. Deutsch (1963) described an example of ground-water contamination by chromium-rich dust discharged through roof ventilators at a factory in Michigan. Accumulating on the downwind side of the plant, the highly soluble hexavalent chromium infiltrated, contaminating a local municipal water supply. Along the Ohio River in the vicinity of Ormet, Ohio, the airborne discharge of fluoride from an aluminum processing plant seriously affected dairy operations, and fluoride concentrations in ground water at the plant exceeded 1,000 mg/L in the mid 1970s.

Ground-Water Quality Problems that Originate Above the Water Table

Many different types of materials are stored, extracted, or disposed of in the ground above the water table. Table 5-1 shows that contamination can originate from many of these operations.

Septic Tanks, Cesspools, and Privies. Probably the major cause of ground-water contamination in the United States is effluent from septic tanks, cesspools, and privies. Individually of little significance, these devices are important in the aggregate because they are so abundant and occur in every area not served by municipal or privately owned sewage treatment systems. Onsite sewage disposal systems number approximately 22 million and discharge an estimated one trillion gallons of effluent. Conventional septic tanks and their associated leach fields account for 85 percent of the systems in use.

The area that each point source affects is generally small, since the quantity of effluent is small, but in some limestone areas effluent may travel long distances in subterranean cavern systems. Biological contamination of ground water is widely recognized. In areas where the density of septic tanks is unusually high and the soils are permeable, this form of waste disposal has caused regional ground-water contamination (Nassau and Suffolk counties, NY, and Dade County, FL).

Surface Impoundments. Surface impoundments, including ponds and lagoons, generally consist of relatively shallow excavations that range in area from a few square feet to many acres. They are used in agricultural, municipal, and industrial operations for the treatment, retention, and disposal of both hazardous and nonhazardous wastes. During the Surface Impoundment Assessment (EPA, 1983), more than 180,000 impoundments were located at approximately 80,000 sites. Nearly half of the sites were located over zones that are either very thin or very permeable, and more than half of these contained industrial waste. In addition, 98 percent of the sites on thick, permeable aquifers were located within a mile of potential drinking water supplies.

Special problems develop with surface impoundments in limestone terrain with extensive near-surface solution openings. In Florida, Alabama, Missouri, and elsewhere, municipal sewage lagoons have collapsed into sinkholes draining raw effluent into widespread underground openings. In some cases the sewage has reappeared in springs and streams several miles away. Wells producing from the caverns could easily become contaminated and cause epidemics of waterborne diseases.

Oil-field brines, which are highly mineralized salt solutions, are particularly noxious and without doubt they have contaminated both surface and ground water in every state that produces oil. The brine, an unwanted by-product, is produced with the oil, as well as during drilling. In the latter case, drilling fluids and brines are stored in reserve pits, which are filled some time after completion or abandonment of the well. Customarily, produced oil-field brines are temporarily stored in holding tanks or placed in an injection well. Owing to the corrosive nature of the brine, leaky tanks and pipelines are not uncommon.

Landfills. Lehman (1986) reported that there are approximately 18,500 municipal and 75,700 industrial landfills that are subject to RCRA Subtitle D regulations. Of the 94,000 known landfills recorded during a 1979 inventory, only about 5,600 facilities were licensed, and the remainder were open dumps (Peterson, 1983).

Sanitary landfills generally are constructed by placing wastes in excavations and covering the material daily with soil—thus the term "sanitary" to indicate that garbage and other materials are not left exposed to produce odors or smoke or attract vermin and insects. Even though a landfill is covered, leachate may be generated by the infiltration of precipitation and surface runoff. Fortunately many substances are removed from the leachate as it filters through the unsaturated zone, but leachate may contaminate ground water and even streams if it discharges at the surface as springs and seeps.

Waste Disposal in Excavations. Following the removal of clay, limestone, sand, and gravel, or other material, the remaining excavations are traditionally left unattended and often used as unregulated dumps. The quantity and variety of materials placed in excavations are almost limitless. They have been used for the disposal of liquid wastes, such as oil-field brines and spent acids from steel mill operations, and for snow removed from surrounding streets and roads—snow that commonly contains a large amount of salt.

Leakage from Underground Storage Tanks. A growing problem of substantial potential consequence is leakage from underground storage tanks and from pipelines leading to them. These facilities store billions of gallons of liquids that are used for municipal, industrial, and agricultural purposes. Corrosion is the most frequent cause for leakage. It has been estimated that at least 35 percent of all underground storage tanks are now leaking (EPA, 1986). Gasoline leakage has caused severe hazardous difficulties throughout the nation. Since gasoline will float on the water table, it tends to leak into basements, sewers, wells, and springs, causing noxious odors, explosions, and fires.

Leakage from Underground Pipelines. Literally thousands of miles of buried pipelines cross the U.S. Leaks, of course, do occur, but they may be exceedingly difficult to detect. Leaks are most likely to develop in lines carrying corrosive fluids. An example occurred in central Ohio where a buried pipeline carried oil-field brine from a producing well to a disposal well. The corrosive brine soon weakened the metal pipe, which then began to leak over a length of several tens of yards. The brine infiltrated, contaminating the adjacent ground water, then flowed down the hydraulic gradient to a stream. During the ensuring months, nearly all of the vegetation between the leaking pipeline and the stream was killed. The leaking area of the pipe was detected only because of the dead vegetation and salty springs. A pipeline that cut through a municipal unconfined well field in south-central Kansas ruptured, spilling a substantial amount of hydrocarbons. Restoration has been both expensive and time consuming.

Sewers are used to transport wastes to a treatment plant. Rarely watertight, fluids leak out of sewers if they are above the water table, and into them if they are in the saturated zone. In many places the water table fluctuates to such a degree that the sewer is gaining in discharge part of the time and losing at other times. Figure 5-2 shows the chloride content in wells 10.5 (D-3) and 14 feet (D-4) deep that are a few feet from a sewer and, upgradient, a 14 feet deep control well (A-4). While the shallower well reached a peak of nearly 175 mg/L, the concentration is much reduced in the deeper well. Even the lowest concentrations near the sewer are 50 percent or more higher than the average background concentration, which is less than 25 mg/L.

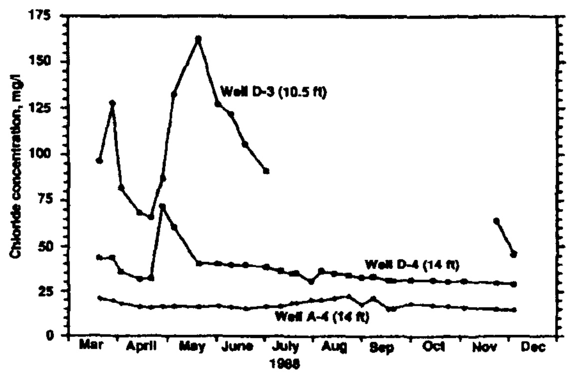

Figure 5-2. Leakage from a Sewer Increases the Chloride Concentration of the Ground Water

Artificial Recharge. Artificial recharge includes an assortment of techniques used to increase the amount of water infiltrating an aquifer. Methods consists of spreading the water over the land or placing it in pits or ponds, or injecting water through wells directly into the aquifer. Waters used for artificial recharge consist of storm runoff, excess irrigation water, streamflow, cooling water, and treated sewage effluent, among others. The quality of water artificially recharged can effect the quality of that in the ground. In several places this has led to increased concentrations of nitrates, metals, detergents, synthetic organic compounds, bacteria, and viruses.

Sumps and Dry Wells. Sumps and dry wells are used for drainage, to control storm runoff, for the collection of spilled liquids, and disposal. They are usually of small diameter and may be filled with pea gravel, coarse sand, or large rocks.

Orr (1990) described several storm water drainage wells in Ohio that receive a variety of contaminants through intentional dumping, illegal disposal, and inadvertent collection of leaks and spills. At Fairfield and Fairborn, dry wells serve as runoff collection wells (an estimated 2,900 in Fairfield) and discharge into very permeable deposits that serve as the major source of domestic, municipal, and industrial water supply. In addition to typical storm water, other contaminants have included used oil and filters, antifreeze, and, in one well, a considerable number of dead catfish. At Fairfield an accidental release of 21,000 gallons of fuel oil from a surface tank flowed into two storm drainage wells in March 1989. Although approximately 16,000 gallons were recovered, by September 1989 ,product thickness in monitoring wells was as much as eight feet.

Graveyards. Leachate from graveyards may cause ground-water contamination, although cases are not well documented. In some of the lightly populated glaciated regions in the north-central part of the U.S., graveyards are commonly found on deposits of sand and gravel, because these materials are easier to excavate than the adjacent glacial till and are better drained so that burials are not below the water table. Unfortunately, these same sand and gravel deposits also may serve as a source of water supply. Graveyards also are possible sources of contamination in many hard rock terrains where there are sinkholes or a thin soil cover.

Ground-Water Quality Problems that Originate Below the Water Table

Table 5-1 lists a number of causes of ground-water contamination produced by the use and misuse of space in the ground below the water table.

Waste Disposal In Wet Excavations. Following the cessation of various mining activities, the excavations usually are abandoned; eventually they may fill with water. These wet excavations have been used as dumps for both solid and liquid wastes. The wastes, being directly connected to an aquifer, may cause extensive contamination. Furthermore, highly concentrated leachates may be generated from the wastes due to seasonal fluctuations of the water table. In the late 1960s at a lead-zinc mine in northwestern Illinois, processing wastes were discharged into an abandoned mine working. The wastes, moving slowly in the ground water, contaminated several farm wells. Analyses of water from several of the wells showed high concentrations of dissolved solids, iron, sulfate, and, more importantly, heavy metals and cyanide.

Agricultural Drainage Wells and Canals. Where surficial materials consist of heavy clay, flat-lying land may be poorly drained and contain an abundance of marshes and ponds. Drainage of this type of land generally is accomplished with field tiles and drainage wells. A drainage well is merely a vertical, cased hole in the ground or in the bottom of a pond that allows the water to drain into deeper, more permeable materials. The drainage water may contain agricultural chemicals and bacteria.

Deepening of stream channels may lower the water table. Where the fresh-saltwater interface lies at shallow depths, lowering of the water table (whether by channelization, pumping, or other causes) may induce upward migration of the saline water; it may even flow into the deepened channel. Under these circumstances, reduction of the depth to fresh water can result in a rise in the level of saline water several times greater than the distance the freshwater level is lowered.

In some coastal areas, the construction of extensive channel networks has permitted tidal waters to flow considerable distances inland. The salty tidal waters infiltrate, increasing the salt content of the ground water in the vicinity of the canal. Some canals are used for the disposal of urban runoff and sewage effluent.

Well Disposal of Wastes. For decades, humans have disposed of liquid wastes by pumping them into wells. Since World War II, a considerable number of deep well-injection projects (Class I wells) have come into existence, usually at industrial sites. Industrial disposal wells range in depth from a few tens of feet to several thousand feet. The injection of highly toxic wastes into some of these wells has led to ground-water contamination. The problems are caused by direct injection into an aquifer, by leakage of contaminants from the well head, through the casing, or via fractures in confining beds.

Exclusive of oil-field brine, most deep well-injection operations are tied to the chemical industry. Well depths range from 1,000 to 9,000 feet and average 4,000 feet. The deepest wells are found in Texas and Mississippi. As of October 1983, EPA reported the existence of at least 188 active hazardous waste injection wells in the United States. There were an additional 24,000 wells used to inject oil-field brine (Class II wells).

Properly managed and designed underground injection systems can be effectively used for storage of wastes deep underground and may permit recovery of the wastes in the future. Before deep well disposal of wastes is permitted by state regulatory agencies and the EPA, however, there must be an extensive evaluation of the well system design and installation, the waste fluids, and the rocks in the vicinity of the disposal well.

Underground Storage. The storage of material underground is attractive from both economic and technical viewpoints. Natural gas is one of the most common substances stored in underground reservoirs. However, the hydrology and geology of underground storage areas must be well understood in order to insure that the materials do not leak from the reservoir and degrade adjacent water supplies.

Secondary Recovery. With increased demands for energy resources, secondary recovery, particularly of petroleum products, is becoming even more important. Methods of secondary recovery of petroleum products commonly consist of injection of steam or water into the producing zone, which either lowers the viscosity of the hydrocarbon or flushes it from the rocks, enabling increased production. Unless the injection well is carefully monitored and constructed, fluids can migrate from a leaky casing or through fractures in confining units.

Mines. Mining has instigated a variety of water contamination problems. These have been caused by pumping of mine waters to the surface, by leaching of the spoil material, by waters naturally discharging through the mine, and by milling wastes, among others. Literally thousands of miles of stream and hundreds of acres of aquifers have been contaminated by highly corrosive mineralized waters originating in coal mines and dumps in Appalachia. In many western states, mill wastes and leachates from metal sulfide operations have seriously affected both surface water and ground water.

Many mines are deeper than the water table, and in order to keep them dry, large quantities of water are pumped to waste. If salty or mineralized water lies at relatively shallow depths, the pumping of freshwater for dewatering purposes may cause an upward migration, which may be intercepted by the well. The mineralized water most commonly is discharged into a surface stream.

Many abandoned underground mine workings serve as a source of water supply for homes, cities, and industry. They also are used as waste receptacles. Orr (1990) described an Ohio situation where combined sanitary sewers and storm water are discharged through wells tapping an abandoned mine. An additional 200 drainage wells were drilled through septic tank leach fields to the underground workings. In the same town, a nationally recognized food processing plant uses the mine for water supply and the city installed their standby well field in it. Water samples from borings into the mine were opaque with sewage, and strong raw sewage and diesel fuel odors were present, along with a strong flow of methane.

Exploratory Wells and Test Holes. Literally hundreds of thousands of abandoned exploratory wells dot the countryside. Many of these holes were drilled to determine the presence of underground mineral resources (seismic shot holes, coal, salt, oil, gas, etc.). The open holes permit water to migrate freely from one aquifer to another. A freshwater aquifer could thus be joined with a contaminated aquifer or a deeper saline aquifer, or contaminated surface water could drain into freshwater zones.

Abandoned Wells. Another cause of ground-water contamination is the migration of mineralized fluids through abandoned wells, and dumping wastes directly into them. In many cases when a well is abandoned the casing is pulled (if there is one) or the casing may become so corroded that holes develop. This permits ready access for fluids under higher pressure to migrate either upward or downward through the abandoned well and contaminate adjacent aquifers. In other cases, improperly cased wells allow high-pressure artesian saline water to spread from an uncased or partly cased hole into shallower, lower-pressure aquifers or aquifer zones.

Although confined aquifers, to some extent, are protected by overlying confining units, abandoned wells make the seal ineffective. In addition, some individuals, probably through a lack of awareness, use abandoned wells to dispose of used motor oil and other liquid wastes, permitting direct access to a drinking water supply.

Water Supply Wells. Improperly constructed water-supply wells may either contaminate an aquifer or produce contaminated water. Dug wells, generally of large diameter, shallow depth, and poorly protected, commonly are contaminated by surface runoff flowing into the well. Other contamination has been caused by infiltration of water through contaminated fill around a well or through the gravel pack. Still other contamination has been caused by barnyard, feedlot, septic tank, or cesspool effluent draining directly into the well. Many contamination and health problems can arise because of poor well construction.

Although well construction standards institute rigid guidelines, they may not be strictly adhered to during the installation of domestic and livestock wells. Furthermore, a great number of water supply wells were constructed long before well standards were established.

Ground Water Development. In certain situations pumping of ground water can induce significant water-quality problems. The principal causes include interaquifer leakage, induced infiltration, and landward migration of sea water in coastal areas. In these situations, the lowering of the hydrostatic head in a freshwater zone leads to migration of more highly mineralized water toward the well site. Undeveloped coastal aquifers are commonly full, the hydraulic gradient slopes towards the sea, and freshwater discharges from them through springs and seeps into the ocean. Extensive pumping lowers the freshwater potentiometric surface permitting sea water to migrate toward the pumping center. A similar predicament which occurs in inland areas where saline water is induced to flow upward, downward, or laterally into a fresh water aquifer due to the decreased head in the vicinity of a pumping well. Wells drilled adjacent to streams induce water to flow from the streams to the wells. If the stream is contaminated, induced infiltration will lead to deterioration of the water quality in the aquifer.

Natural Controls on Ground-Water Contamination

As Deutsch (1965) clearly pointed out, there are four major natural controls involved in shallow ground-water contamination. The first includes the physical and chemical characteristics of the earth materials through which the liquid wastes flow. A major attenuating effect for many compounds is the unsaturated zone. Many chemical and biological reactions in the unsaturated zone lead to contaminant degradation, precipitation, sorption, and oxidation. The greater the thickness of the unsaturated zone, the more attenuation there is likely to take place. Below the water table, the mineral content of the medium probably becomes more important because assorted clays, hydroxides, and organic matter take up some of the contaminants by exchange or sorption. Many of the other minerals have no effect on the contaminants with which they come into contact.

The second major control includes the natural processes that tend to remove or degrade a contaminant as it flows through the subsurface from areas or points of recharge to zones or points of discharge. These processes include filtration, sorption, ion-exchange, dispersion, oxidation, and microbial degradation, as well as dilution. The third control relates to the hydraulics of the flow system through which the waste migrates, beginning with infiltration and ending with discharge. The contaminant may enter an aquifer directly, by flowing through the unsaturated zone, by interaquifer leakage, by migration in the zone of saturation, or by flow through open holes.

The final control is the nature of the contaminant. This includes its physical, chemical, and biological characteristics and, particularly, its stability under varying conditions. The stability of the more common constituents and the heavy metals are fairly well known. On the other hand, the stability of organic compounds, particularly synthetic organic compounds, has only recently come under close inspection and actually little is known of their degradation and mobility in the subsurface. This fact has been brought clearly to the attention of the general public by the abundance of reported incidences of contamination by EDB, TCE, and DBCP.

To a large extent, it is the aquifer framework that controls the movement of ground water and contaminants. Of prime importance, of course, is the hydraulic conductivity, both primary and secondary. In the case of consolidated sedimentary rocks, primary permeability, in many respects, is more predictable than secondary permeability. In sedimentary rocks, similar units of permeability tend to follow bedding planes or formational boundaries, even if the strata are inclined. Permeable zones most often are separated by layers of fine-grained material, such as clay, shale, or silt, which serve as confining beds. Although leakage through confining beds is the rule rather than the exception, both water and contaminants are more likely to remain in a permeable zone than to migrate through units of low permeability. The movement of ground water and contaminants through larger openings, such as fractures, complicates the assumed picture. Not only can the velocity change dramatically, but in fracture flow, much of the attenuation capacity is lost, and it is difficult to predict local directions of flow.

The geologic framework, in conjunction with surface topography, also exerts a major control on the configuration of the water table and the thickness of the unsaturated zone. Generally speaking, the water table would be relatively flat in a deposit of permeable surficial sand and gravel. In contrast, the water table in glacial till, which is typically fine-gained, would more closely conform to the surface topography. The position of the water table is important not only because it is the boundary between the saturated and unsaturated zones, but also because it marks the bottom and, therefore, the thickness of the unsaturated material.

In many, if not most, contaminated areas, the water table has been or is intermittently affected by pumping. The resulting cone of depression on the water table changes both the hydraulic gradient and ground-water velocity. A change in gradient and velocity also occurs in the vicinity of recharge basins (lagoons, pits, shafts, etc.), because the infiltrating water forms a mound in the water table. As Figure 5-3 shows, the mound causes radial flow and, therefore, contaminants can move in directions that are different than the regional hydraulic gradient, at least until the mounding effects are overcome by the regional flow.

Ground-water or interstitial velocity is controled by the hydraulic conductivity, gradient, and effective porosity. Water movement through a permeable gravel with a gradient of 10 feet per mile averages about 60 feet per day, but in a clay with the same gradient and no secondary permeability the water movement would be only about 1 foot in 30,000 years. In most aquifers, ground-water velocity ranges from a few feet per day to a few feet per year.

Carlston (1964) determined that the mean residence time of ground water in a basin in Wisconsin was about 45 days and in New Jersey about 30 days. This study shows that ground water may discharge into closely spaced streams in humid areas within a few days to a few months. On the other hand, in less permeable terrains ground water and contaminants may remain in the subsurface for years or even decades.

Leachate

The causes of ground-water contamination are many, but it is the source that needs special consideration. For example, an accidental spill from a ruptured tank may provide a considerable volume of liquid with an extremely high concentration that is present only during a short time, but leachate continuously generated from a landfill may consist of a large volume of low concentration that spans many years. Once it reaches the water table, a spill might move largely as a conservative contaminant because of its high concentration, despite the fact that it might be degradable in smaller concentrations. Leachate is more likely to be attenuated by microbial degradation, sorption, dilution, and dispersion.

In the case of landfills and similar sources, leachate is a liquid that has formed as infiltrating water migrates through the waste material extracting water-soluble compounds and particulate matter. The mass of leachate generated is directly related to precipitation, assuming the waste lies above the water table. Much of the annual precipitation, including snowmelt, is removed by surface runoff and evapotranspiration; it is only the remainder

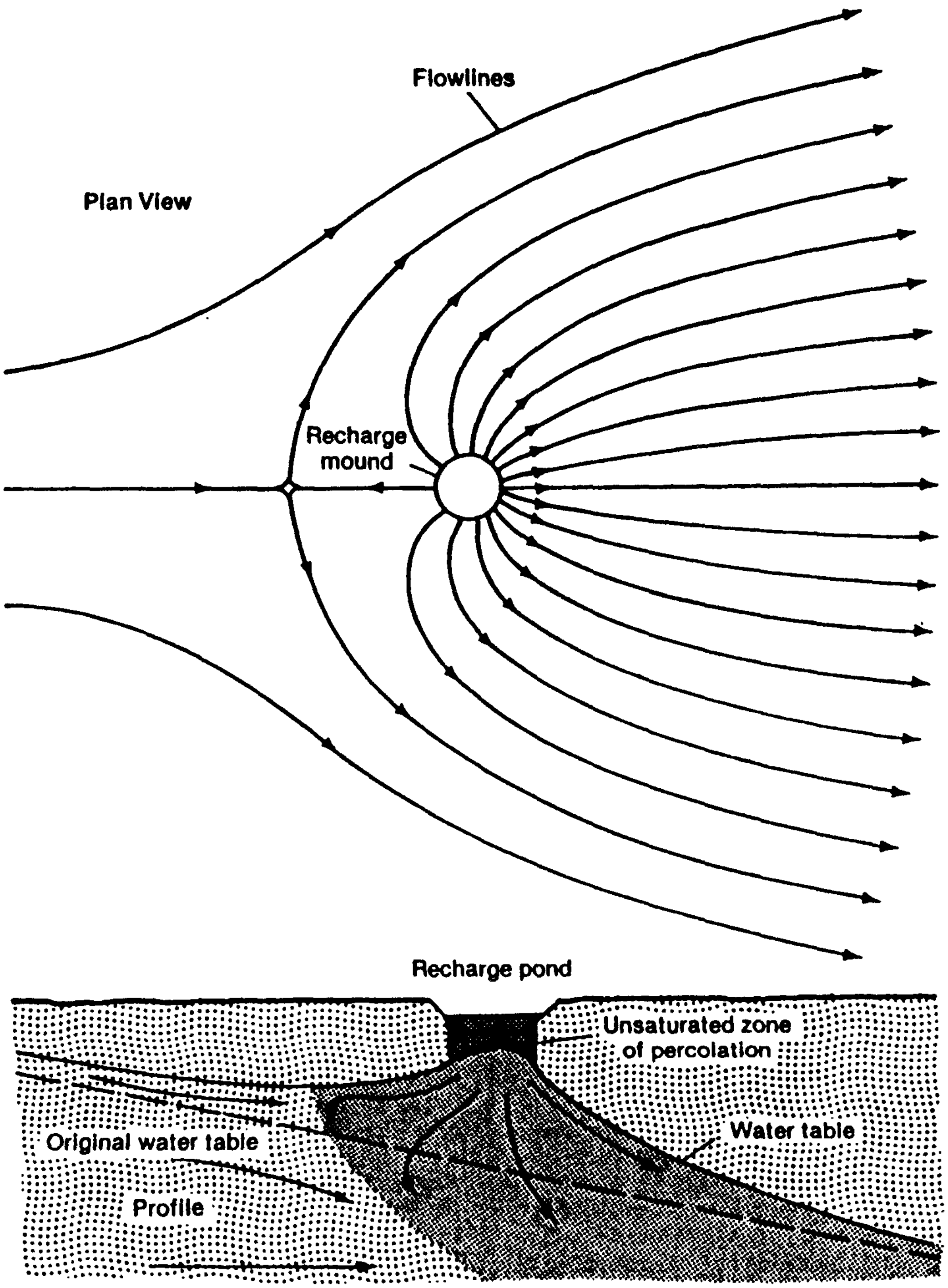

Figure 5-3. Infiltration from a Surface Impoundment Will Create a Mound on the Water Table

that is available to form leachate. Since the landfill cover, to a large extent, controls leachate generation, it is exceedingly important that a cover be properly designed, maintained, and monitored.

The physical, chemical, and biological characteristics of leachate are influenced by: (1) the composition of the waste, (2) the stage of decomposition, (3) microbial activity, (4) the chemical and physical characteristics of the soil cover and of the landfill, and (5) the time rate of release (recharge). Since all of the above can range within remarkably wide limits, it is possible to provide only a general range in concentration of leachate constituents, as Table 5-2 shows.

Constituents	Operating Landfill	Abandoned Landfill
BOD_5, mg/L	1,800	18
COD, mg/L	3,850	246
Ammonia-N, mg/L	160	100
Hardness, mg/L as $CaCO_3$	900	290
Total iron, mg/L	40.4	2.2
Sulfate, mg/L	225	100
Specific Conductance, µmhos	3,000	2,500

Table 5-2. Comparison of Chemical Characteristics of Leachate from an Operating Landfill and a 20-Year-Old Abandoned Landfill in Southeastern Pennsylvania (From Wu and Ahlert, 1976)

It also is important to account for the fact that materials placed in landfills may vary seasonally. For example, many municipal landfills are used to dispose of snow and ice, which may contain calcium, sodium, and chloride from de-icing salts. This could lead to the generation of leachate that changes throughout the year, particularly in regard to the chloride concentration. In addition, leachate collected from a seep at the base of a landfill should be more highly mineralized than that present in the underlying ground water, which is diluted.

Changes in Ground-Water Quality

It is often assumed that natural ground-water quality is nearly constant at any particular site. Field data substantiate this assumption, and logic leads to the same conclusion, if the aquifer is confined and not subjected to a stress. Multiple samples from a single well, however, are likely to show slight changes in concentrations of specific constituents owing to differences in sample collection, storage, and analytical technique.

Deeper or confined aquifers in which ground-water flow is lethargic, generally have a nearly constant chemical quality that, at any particular place, reflects the geochemical reactions that occurred as the water migrated through confining layers and aquifers from recharge area to points of collection or discharge.

The quality of deeper water can change, but generally not abruptly, in response to stresses on the aquifer system. Changes in hydrostatic head brought about by pumping, for example, may cause migration of other types of waters from adjacent units into the producing zone. As shown in Figure 5-4, the sulfate content of a municipal well in north-central North Dakota increased fivefold, from 200 to 1,000 mg/L, over a period of a few years.

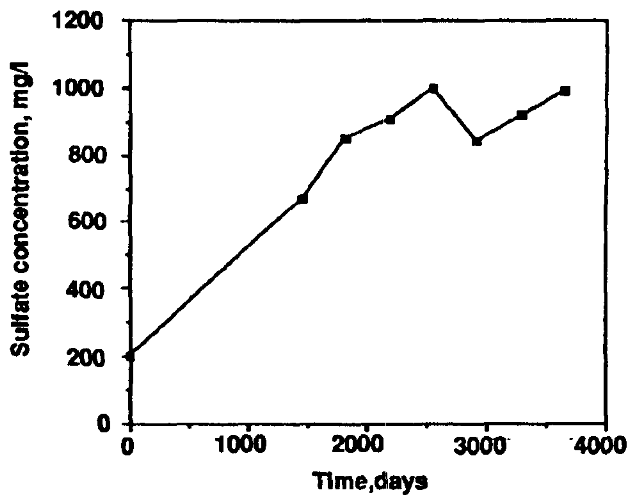

Figure 5-4. The Increase in Sulfate Concentration Was Related to Natural Causes Brought About by Pumping

In this instance, the first sample was collected in 1974 when the well was first pumped for an acceptance test. The well, one of six in a new field, tapped a previously unused and confined ground-water system. By 1978 the entire well field was in operation, overlapping cones of depression had spread out several miles along the trend of the buried glacial valley, and the sulfate concentration had increased to nearly 700 mg/L. From 1982 through 1985 sulfate fluctuated between about 850 and 1,000 mg/L, and the slow change, either an increase or a decrease, was in response to the pumping durations and rates of all of the wells in the field. The source of the naturally occurring sulfate was several hundred feet from the nearest production well and, fortunately, only one other well was affected, and then to a far smaller degree. Consequently, it was possible to blend the water from all of the production wells, and the concentration of sulfate in the mixed water consistently was less than 250 mg/L.

Changes in water quality in confined aquifers also may be due to fluid migration along the well casing or gravel pack, or by leakage through confining beds, abandoned wells, or exploration holes, and by well injection of waste fluids.

In contrast to confined aquifers, ground-water quality, in shallow and surficial aquifers, can change considerably within a few hours or days. These aquifers are not well protected from changes brought about by natural events occurring at the land surface or from human-induced contamination. Surficial aquifers, in fact, are highly susceptible to rapid and sometimes dramatic changes in quality.

In the majority of cases, neither water levels nor water samples are measured or collected at regular intervals. Annual or quarterly measurements or samples may be satisfactory for most purposes, but they are likely to be far too infrequent in ground-water studies if an investigator is attempting to develop an understanding of the manner in which a system functions. Figure 5-5 shows the March through December 1988 fluctuation of the water table in a well 14 feet deep. Quarterly measurements provide a good indication of the annual

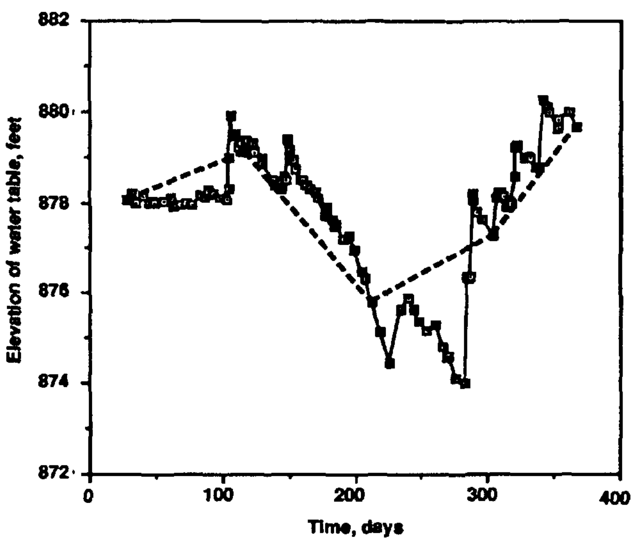

Figure 5-5. Weekly Water-Table Measurements More Accurately Show the Aquifer Response than do Quarterly Measurements

change, but they do not display the complexity of the hydrograph, as shown by weekly measurements. It is the short-term rise in water level that is most likely to indicate changes in ground-water quality.

Figure 5-6 shows the annual range in electrical conductivity in the same well described above. Again, quarterly measurements provide a general impression of the change throughout the year, which in this example is from about 925 to 1,070 μmhos. On the other hand, an average of five measurements per month reveal that the electrical conductivity changed considerably from one time to the next, and that the annual range is from 800 to 1,175 μmhos.

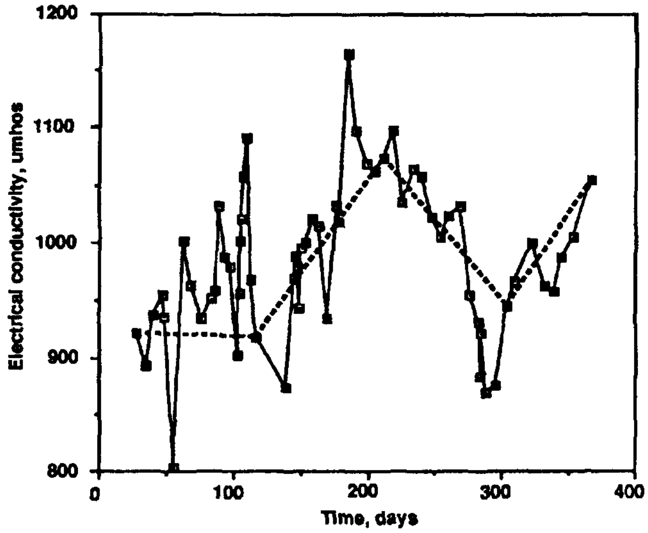

Figure 5-6. Weekly Measurements of Electrical Conductivity are more useful for Determining Changes in Chemical Quality than are Quarterly Determinations

The Concept of Cyclic Fluctuations

Several years ago, Pettyjohn (1971,1976, 1982) described cyclic fluctuations of ground-water quality. The mechanisms that lead to cyclic fluctuations will be discussed in greater detail here because both the cause and effect can have a significant impact on: (1) ground-water quality monitoring and determination of background quality; (2) transport and fate of organic and inorganic compounds, as well as bacteria and viruses; and (3) monitoring well design and installation.

The contaminated site that Pettyjohn used to develop the concept of cyclic fluctuation lies on the flood plain of the Olentangy River in central Ohio where precipitation averages about 38 inches per year (fig. 5-7). Underlain by shale, the alluvial deposits consist of 15 to 35 feet of sand, gravel, silt, and clay. The water table, 1.5 to 5 feet below land surface, oscillates a foot or so annually.

Oil production began at this site in mid-1964, but by July 1965, all wells had been plugged. Ground-water contamination occurred because of leakage of oil-field brine, containing about 35,000 mg/L of chloride, from three holding ponds. When samples were first collected from 23 monitoring wells in July 1965, the aquifer locally contained more than 35,000 mg/L of chloride.

Of particular importance in the monitoring of this site is a cluster of three wells, one screened at a depth of 7 to 9 feet and another from 21 to 23 feet, while a third, gravel-packed through much of its length (23 feet), receives water from the entire aquifer (fig. 5-8). It is assumed that the third well provides a composite sample of the reservoir and that when it had a higher concentration than both the deep and shallow wells, the most highly mineralized water was between 9 and 23 feet, and vice versa.

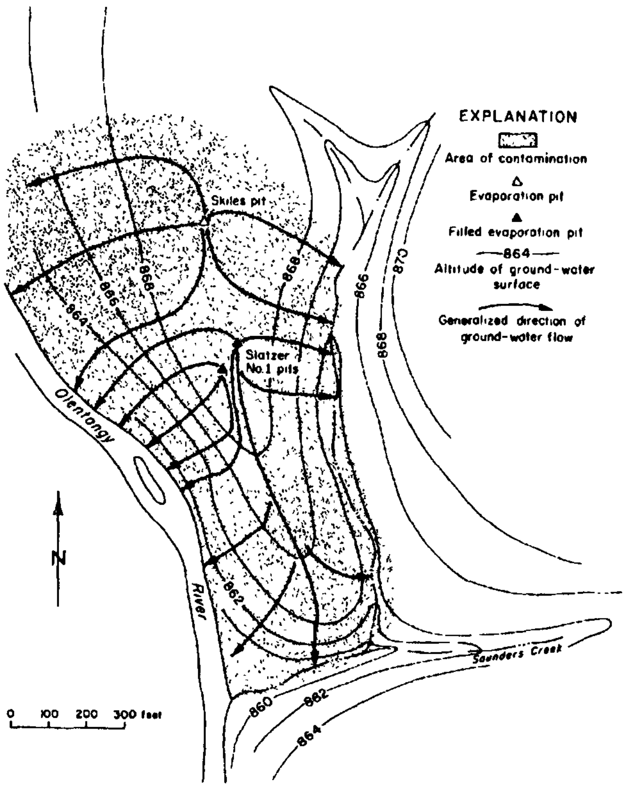

Figure 5-7. Water-Table Map of the Contaiminated Olentangy River Site

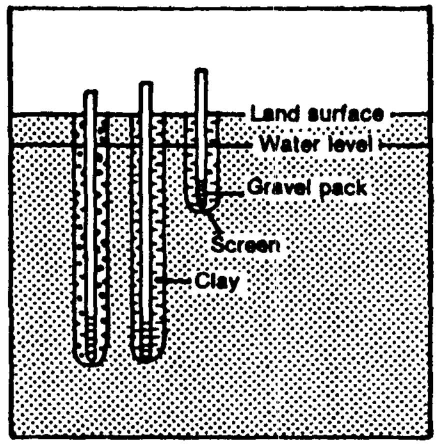

Figure 5-8. Construction Details of Three Wells in a Cluster

Figure 5-9 shows the chloride fluctuations in the three ns occurred at the shallowest depths, at other times at the greatest depth, and at still other times the greatest concentration was somewhere in the middle of the aquifer. Figures 5-10 and 5-11 show the vertical distribution of chloride in the aquifer. The only means for accounting for the variable distribution, both in space and time, is intermittent recontamination, which is puzzling in view of the fact that oil-field activities ceased in June 1965 before any of the samples were collected.

The chloride fluctuations that occurred during 1965 to 1966 and 1969 are shown schematically in Figure 5-12. The October 1965 samples apparently were collected shortly after a recharge event, which leached salt from the unsaturated zone. This slowly sinking mass (1) was subsequently replaced with less mineralized water. A month later, the first mass had reached and was migrating along the bottom of the aquifer when another recharge event occurred (2). By December, the second mass had reached the bottom of the aquifer and was moving toward the river. Recharge events also occurred in January 1966 (3), and in February 1966 (4). Figure 5-12 shows that the aquifer was recontaminated several times during 1969, particularly during January, February, and March. On the average, it appears that the chloride concentration in the ground water at the Olentangy River site was reduced by half every 250 or so days. This was not a linear decline, but rather intermittent flushing of the source.

Findings similar to those in the Olentangy River study have been reported by Hagen (1986), Hoyle (1987), Ross (1988), Pettyjohn (1987a, 1987b, 1988), Pettyjohn and others (1986), Nelson (1989), and Froneberger

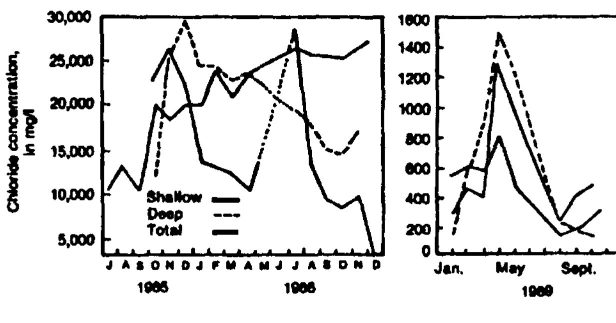

Figure 5-9. Variations in Chloride Concentration in Cluster Wells at the Olentangy River Site

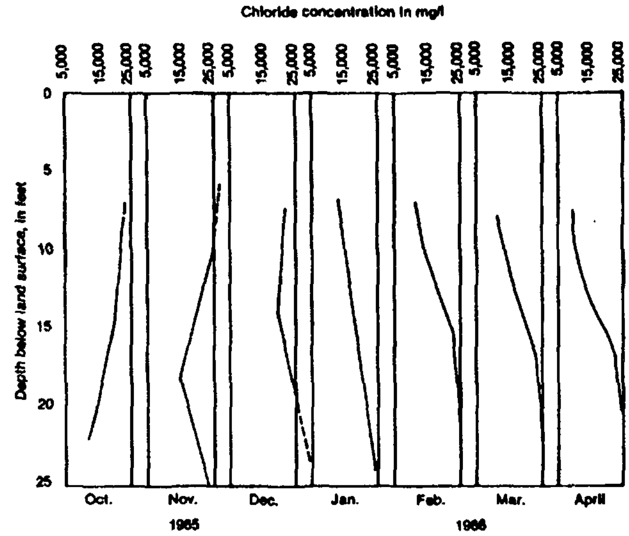

Figure 5-10. Vertical Distribution of Chloride During 1965 and 1966

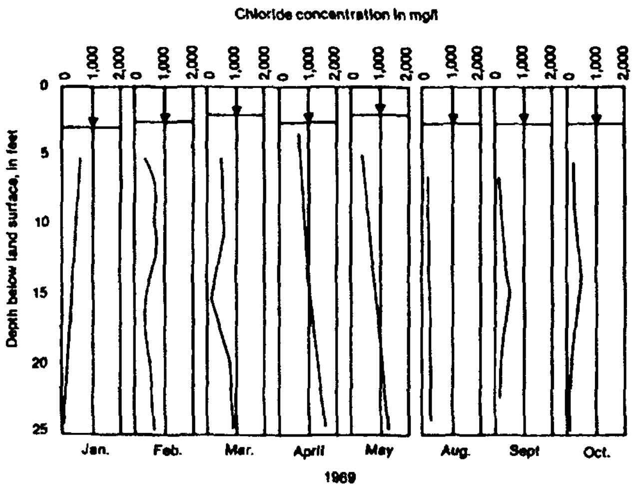

Figure 5-11. Vertical Distribution of Chloride During 1969

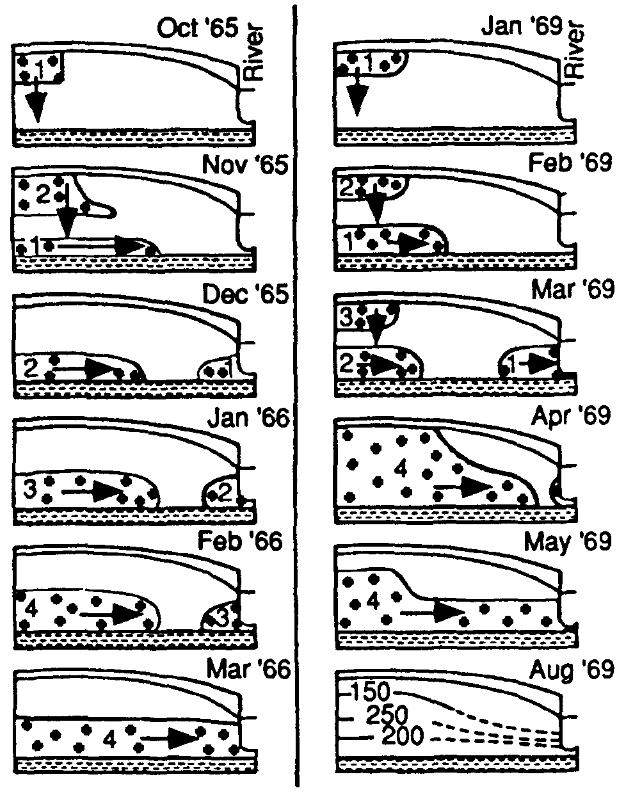

Figure 5-12. Conceptual Model Showing Leaching and Recontamination of Ground Water at the Olentangy River Site

(1989). The investigations were conducted in an urban area in north-central Oklahoma at a small but intensely monitored field site. The site lies on the flood plain of a small stream, and the alluvium consists of a fine-grained silt loam that contains soil structures throughout the entire thickness of 43 feet.

At the Oklahoma site, fertilizer application, followed by rain, has a short lived but significant effect on the concentration of nitrogen in ground water, regardless of the soil-moisture content. As Figure 5-13 shows, nitrate concentrations increased in one well (14 feet deep) from about 4 to to 16 mg/L within a two-day period following 1.3 inches of rain. The concentration then decreased to about 2 mg/L during the next three days. At this time (September 1985) the soil-moisture content was very low. The change in nitrate concentration over the five-day interval appears to suggest the infiltration of a relatively small volume of highly concentrated water that is followed about two days later with a large volume of water with a very low nitrate content. Flow through the unsaturated zone was greater than 5 feet per day, suggesting early flow through macropores that is followed by piston-type flow.

A similar phenomenon occurred in April 1986 when the soil-moisture content was twice as great as it had been in September, 1985. Shown in Figure 5-14 is the nitrate concentration in three wells at a cluster; the wells are 8.5 (A-1), 9.5 (A-2), and 14 (A-4) feet deep. The change in concentration in all of the wells follows the same pattern, but the concentration decrease with depth. Following a rain, the concentration at a depth of 8.5 feet, for example, increased only about 3 mg/L and this was followed during the next two days by a decrease of 15 mg/L and then nitrate again slowly increased.

During the fall and spring events, nitrate accounted for only a small percentage of the dissolved solids content, and the concentration of the other major constituents in the water followed a different pattern. As Figure 5-15 shows, there was a small decrease in electrical

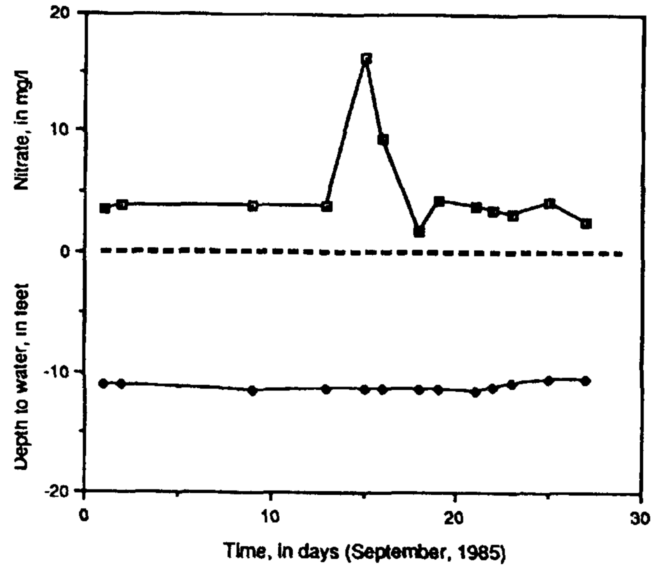

Figure 5-13. During Dry Weather the Water-Table Aquifer Responded Quickly to Rain and Flushed Nitrate into the Ground

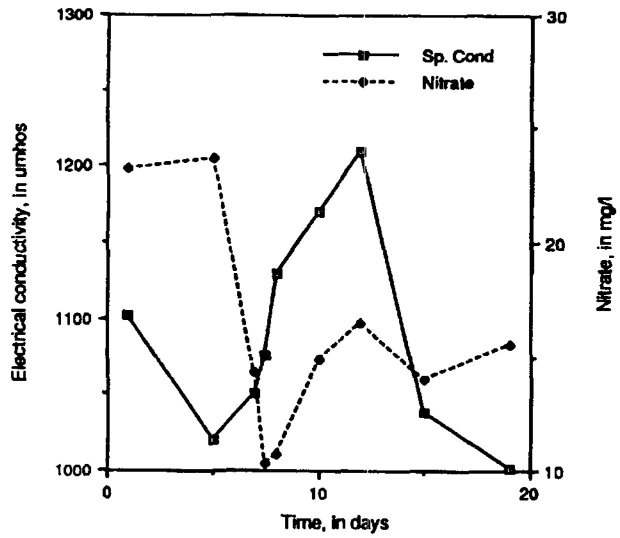

Figure 5-15. The Increase in Nitrate Was Caused by a Small Volume of Rapidly Infiltrating Water, While the Later Increase in Electrical Conductivity Was Caused by a Large Mass of Slowing Moving Water

conductivity at the peak nitrate concentration, and as the nitrate decreased, electrical conductivity began to increase, reaching a maximum about 11 days later.

At the same site, another well cluster, adjacent to a building, receives runoff from the roof that infiltrates in the vicinity of the wells. The runoff has a low dissolved mineral content and, when it infiltrates during a prolonged wet period, the electrical conductivity of the ground water decreases from around 1,000 to about 400 µmhos (fig. 5-16).

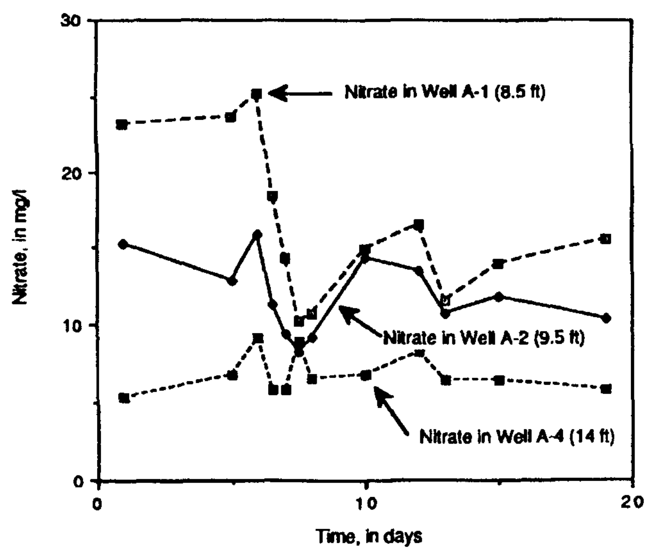

Figure 5-14. Although Decreasing with Depth, Nitrate Concentrations in all of the Wells Followed a Similar Pattern after a Rain

The Ohio and Oklahoma studies indicate that water soluble substances on the land surface or in the unsaturated zone may be intermittently introduced into a shallow aquifer, changing its quality, for many years. The rate of introduction or leaching is dependent upon the chemical and physical properties of the waste and the soil, and the frequency of the recharge events.

Throughout most of the year in humid and semiarid regions, the quantity of water that infiltrates and the amount of contaminants that are flushed into an aquifer are relatively small. During summer months, ground-water quality changes would be expected to occur more rapidly, perhaps in a matter of hours, because of the large size and abundance of the macropores and fractures. These changes, however, may occur only over a relatively small area because of the local nature of convective storms.

On the other hand, during the spring recharge period and, in many places, during the fall as well, noteworthy quantities of contaminants may infiltrate over wide areas. Although the quantity of leached substances is larger than at any other time during the year, the change may occur more slowly and the resulting concentration in ground water may not be at a maximum because of the diluting effect brought about by the major influx of water. Therefore, the major infusion of contaminants, which is strongly influenced by climate, occurs twice a year, although minor recharge events may occur at any time.

This phenomenon has important implications in

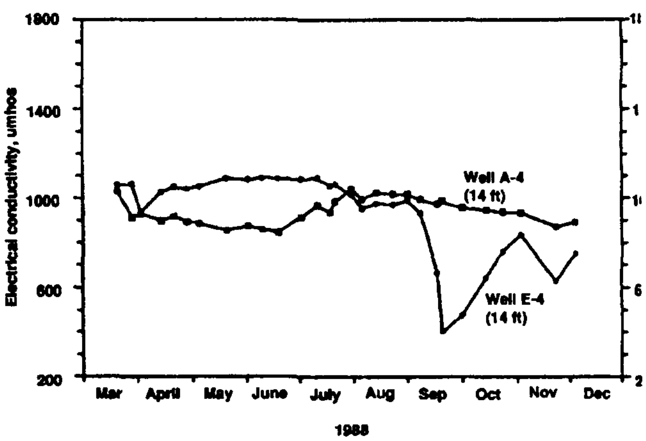

Figure 5-16. Runoff from a Roof Tends to Reduce the Electrical Conductivity of the Underlying Ground Water

monitoring and sampling. Since the natural quality of shallow ground water ranges fairly widely, background concentration is not a finite number but, rather, a range that may encompass an order of magnitude for major constituents, such as dissolved solids, and two or three orders of magnitude for minor forms, such as nitrate. In addition, the concentration might increase several fold a day or two after a rain, or decrease even more three to five or so days later. The question then arises as to the most appropriate time to sample. Available data suggest that the least biased sample could be obtained at least two weeks after a recharge event, but the interval is strongly influenced by the physical and chemical characteristics of the unsaturated zone and the depth to the water table.

In order to account for cyclic fluctuations in ground-water quality it is assumed that: (1) the unsaturated zone may store a considerable volume of water-soluble substances for long periods of time, and (2) the main paths along which contaminants rapidly move through the unsaturated zone to the water table consist largely of fractures and macropores.

Most macropores may be barely detectable without a close examination. Ritchie and others (1972) suggested that the interfaces between adjacent soil peds also serve as macropores. Moreover, these openings need not extend to the land surface in order for flow to occur in them (Quisenberry and Phillips, 1976). Nonetheless, water can flow below the root zone in a matter of minutes. Thomas and Phillips (1973) suggested that this type of flow does not appear to last more than a few minutes or perhaps, in unusual cases, more than a few hours after "cessation of irrigation or rain additions."

Even though there may be a considerable influx of contaminants through macropores and fractures to the water table following a rain, the concentration of solutes in the main soil matrix may change little, if at all. This is clearly indicated in studies by Shuford and others (1977) and again shows the major role of large openings. On the other hand, in the spring, when the soil-moisture content is high, some of the relatively immobile or stagnant soil water may percolate to the water table transporting salts with it. A similar widespread event may occur during the fall as a result of decreasing temperature and evapotranspiration, and of wet periods that might raise the soil-moisture content.

Ecologic conditions in fractures and macropores should be quite different from those in the main soil matrix, largely because of the greater abundance of oxygen and smaller moisture content. As a result, one might expect different microbial populations and densities, as well as chemical conditions in macropores and fractures than in the bulk soil matrix. Coupled with their far greater fracture permeability, this may help to explain why some biodegradable organic compounds or those that should be strongly sorbed actually reach the water table and move with the ground water.

Prediction of Contaminant Migration

In any ground-water contamination investigation it is essential to obtain the background concentration of the chemical constituents of concern, particularly those that might be common both to the local ground water and a contaminant. As mentioned previously, the water in shallow or surficial aquifers can undergo substantial fluctuations in chemical quality. Therefore, it is not always a simple task to determine background concentrations, particularly of the more conservative constituents, such as chloride or nitrate.

The severity of ground-water contamination is partly dependent on the characteristics of the waste or leachate, that is, its volume, composition, concentration of the various constituents, time rate of release of the contaminant, the size of the area from which the contaminants are derived, and the density of the leachate, among others. Data describing these parameters are difficult to obtain and commonly are lumped together into the term "mass flow rate," which is the product of the contaminant concentration and its volume and recharge rate, or leakage rate.

Once a leachate is formed it begins to migrate downward through the unsaturated zone where several physical, chemical, and biological forces act upon it. Eventually, however, the leachate may reach saturated strata where it will then flow primarily in a horizontal direction as defined by the hydraulic gradient. From this point on, the leachate will become diluted due to a number of phenomena, including filtration, sorption, chemical processes, microbial degradation, dispersion, time, and distance of travel.

Filtration removes suspended particles from the water mass, including particles of iron and manganese or other precipitates that may have been formed by chemical reaction. Dilution by sorption of chemical compounds is caused largely by clays, metal oxides and hydroxides, and organic matter, all of which function as sorptive material. The amount of sorption depends on the type of contaminant and the physical and chemical properties of the solution and the subsurface material.

Chemical processes are important when precipitation occurs as a result of excess quantities of ions in solution. Chemical processes also include volatization as well as radioactive decay. In many situations, particularly in the case of organic compounds, microbiological degradation effects are not well known, but it does appear, however, that a great deal of degradation can occur if the system is not overloaded and appropriate nutrients are available (see Chapter 7).

Dispersion of a leachate in an aquifer causes the concentration of the contaminants to decrease with increasing length of flow. It is caused by a combination of molecular diffusion, which is important only at very low velocities, and dispersion or hydrodynamic mixing, which occurs at higher velocities in laminar flow through porous media. In porous media, different macroscopic velocities and flow paths that have various lengths are to be expected. Leachate moving along a shorter flow path or at a higher velocity would arrive at an end point sooner than that part following a longer path or a lower velocity; this results in hydrodynamic dispersion.

Dispersion can be both longitudinal and transverse and the net result is a conic form downstream from a continuous contamination source. As Figure 5-17 shows, the concentration of the leachate is less at the margins of the cone and increases toward the source. Because dispersion is directly related to ground-water velocity, the size of a plume of contamination tends to increase with more rapid flow.

Since dispersion is affected by velocity and the configuration of the aquifer's pore spaces, coefficients must be determined experimentally or empirically for a given aquifer. There is considerable confusion regarding the quantification of the dispersion coefficient. Selection of dispersion coefficients that adequately reflect conditions that exist in an aquifer is a problem that can

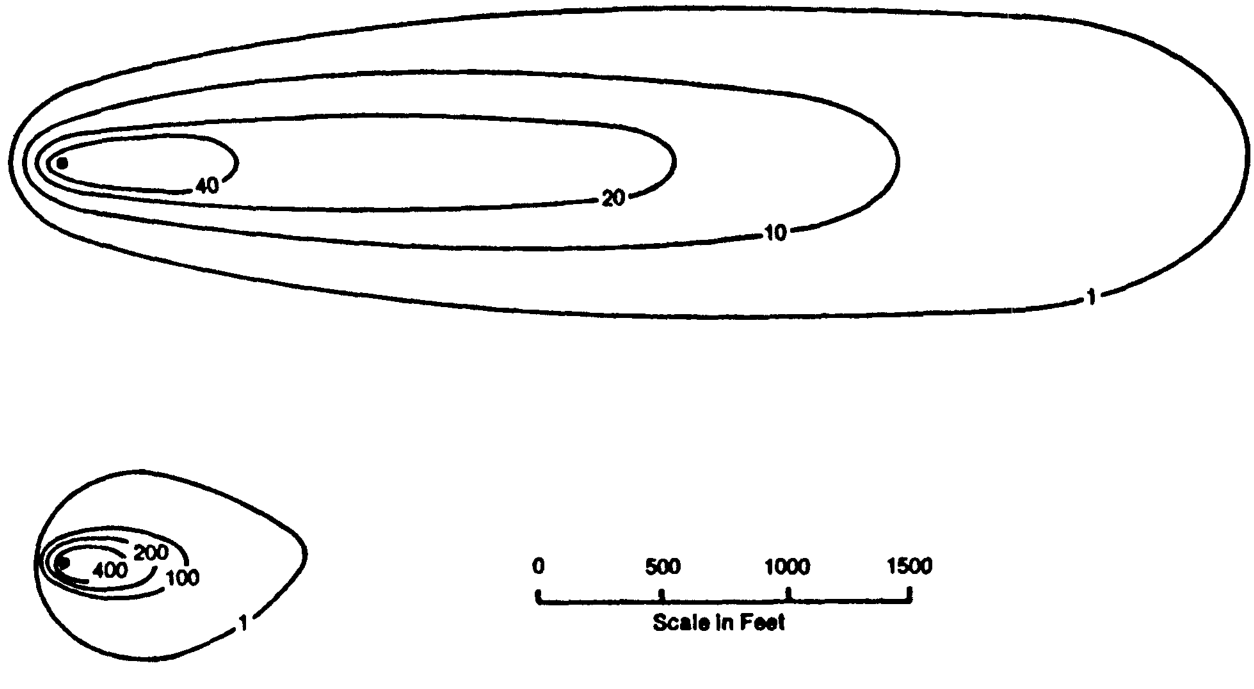

Figure 5-17. The Size and Concentration Distribution in a Contaminant Plume is Related to Ground-Water Velocity. Upper Plume Velocity is 1.5 feet/day; in lower Plume Velocity is 0.5 feet/day

not be readily solved and herein lies one of the major stumbling blocks of chemical transport models.

Often confused with the term dispersion (D_x = longitudinal dispersion and D_y = transverse dispersion) is dispersivity. Dispersion includes velocity: to transform from one to another requires either division or multiplication by velocity.

The rate of advance of a contaminant plume can be retarded if there is a reaction between its components and ground-water constituents or if sorption occurs. This is called retardation (R_d). The plume in which sorption and chemical reactions occur generally will expand more slowly and the concentration will be lower than the plume of an equivalent nonreactive leachate.

Hydrodynamic dispersion affects all solutes equally while sorption, chemical reactions, and microbial degradation affects specific constituents at different rates. As Figure 5-18 shows, a leachate source that contains a number of different solutes can have several solutes moving at different rates due to the attenuation processes.

The areal extent of plumes may range within rather wide extremes depending on the local geologic conditions, influences on the hydraulic gradient, such as pumping, ground-water velocity, and changes in the time rate of release of contaminants.

The many complex factors that control the movement of leachate and the overall behavior of contaminant plumes are difficult to assess because the final effect represents several factors integrated collectively. Likewise, concentrations for each constituent in a complex waste are difficult to obtain. Therefore, predictions of concentration and plume geometry, at best, can only be used as estimates, principally to identify whether or not a plume might develop at a site and, if so, to what extent. Models can be used to study plume migration, and as an aid in determining potential locations for monitoring wells, and to test various renovation or restoration schemes.

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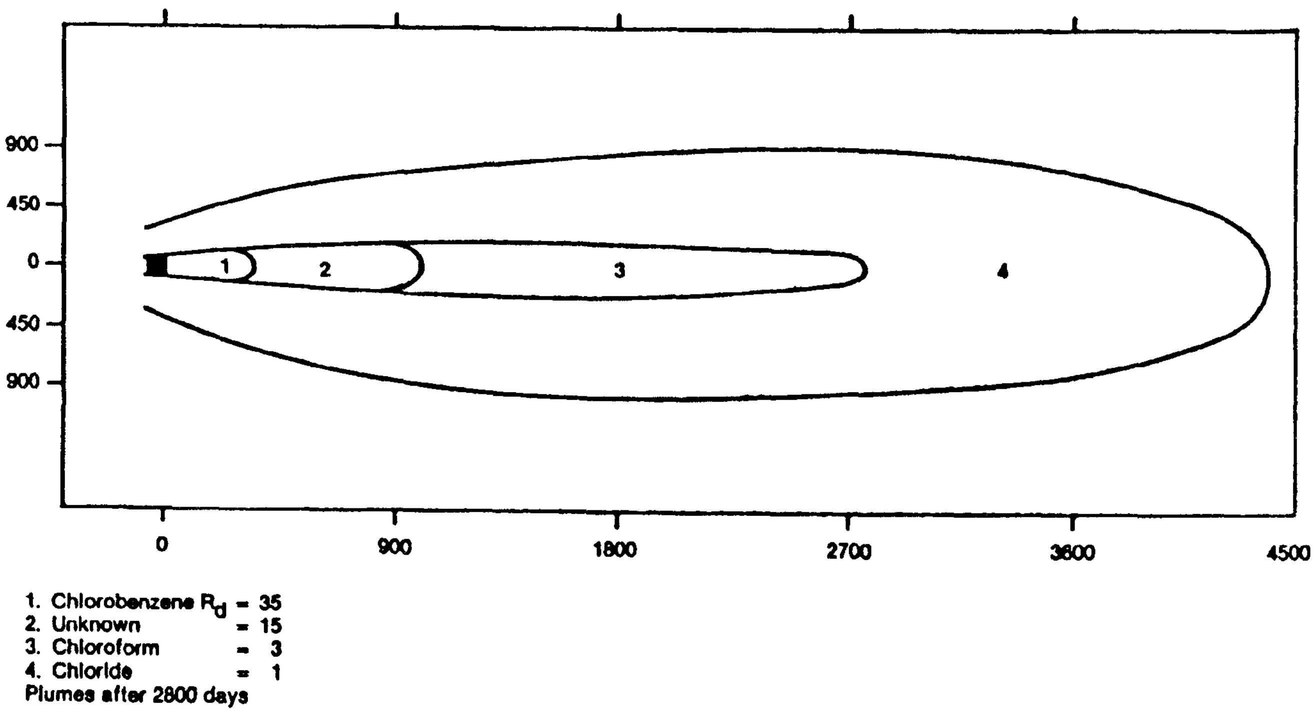

Figure 5-18. Constituents Move at Different Rates Because of Retardation

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Chapter 6

GROUND-WATER INVESTIGATIONS

Introduction

Within the last decade, a substantial number of ground-water investigations have been conducted. Many of these have been centered at specific contaminated sites in response to federal legislation concerned with sources of drinking water, threats to human health and the environment posed by toxic and hazardous waste, and the restoration of contaminated aquifers. In general, most of the sites consist of only several acres or a few square miles, but a number of reconnaissance studies have focused on thousands of square miles.

In most cases the cost of these investigations has been excessively high, due in large measure to the expense of analytical services. The most disconcerting feature of many of these investigations is that their results were found to be inadequate, and additional work and expense were required. It must be understood that a data base will almost always be inadequate to some and its resolution will eventually be dictated by time, common sense, and budgetary constraints. Although these constraints will always be present to one degree or another, it is imperative that the most reliable and applicable information be collected commensurate with the available resources.

The reason many field investigations are both inadequate and costly is that a comprehensive work plan was not developed before the project was initiated, or that it was not followed. Any type of an investigation must be carefully planned, keeping in mind the overall purpose, time limitations, and available resources. Moreover, the plan must use a practical approach based on sound, fundamental principles. As far as ground-water quality investigations are concerned, the basic questions are (1) is there a problem, (2) where is it, and (3) how severe is it? A subsequent question may relate to what can be done to reduce the severity, that is, aquifer restoration.

Ground-water quality investigations can be divided into three general types: regional, local, and site evaluation. The first, which may encompass several hundred or even thousands of square miles, is reconnaissance in nature, and is used to obtain an overall evaluation of the ground-water situation. A local investigation is conducted in the vicinity of a contaminated site, may cover a few tens or hundreds of square miles, and is used to determine local ground-water conditions. The purpose of the site evaluation is to ascertain, with a considerable degree of certainty, the extent of contamination, its source or sources, hydraulic properties, and velocity, as well as all of the other related controls on contaminant migration.

Ground-water investigations can be quite varied in terms of purpose as well as scale and duration. Although a few of these variations will be discussed briefly, the main topic of this chapter will be site specific ground-water investigations involving contamination with toxic and hazardous wastes.

Purposes of Ground-Water Investigations

Ground-water investigations are conducted for a variety of purposes. One is for reconnaissance or the establishment of background quality, such as those done by the U. S. Geological Survey for many years, which resulted in a historical documentation of the quality and quantity of both surface and subsurface waters. Usually these investigations are made using existing private, municipal, industrial, and irrigation wells. The data are useful for determining fluctuations, trends, and cycles in water levels and chemical quality.

Another purpose may be to monitor a variety of ground-water parameters in order to establish cause and effect relationships, as for example, an assessment of the design, construction and operation of a hazardous waste disposal facility on areal ground-water quality. Monitoring may be done to assure the integrity of lagoon liners or, in general, prove compliance with any of the regulatory standards dealing with waste disposal, storage, or treatment facilities. Ground-water quality monitoring also is increasing with respect to possible contaminant sources, such as underground storage tanks, the application of agricultural chemicals, and mining, just to mention a few.

Ground-water investigations traditionally have played an important role in litigation. Under the civil laws of trespass or negligence, the information obtained during a study may be used to determine the source of ground-water contamination in order to establish liability, or be used in response to federal legislation, such as RCRA and Superfund. In these cases particular attention must be given to the handling of samples as well as the documentation of field and laboratory procedures. During the beginning of the study, legal counsel should be obtained to assure that proper procedures are built into the work plan.

Perhaps the most specialized types of ground-water investigations are those driven by research objectives. The goals of these studies are as varied as the nature of research itself, and may range from model validation to determining the rates and daughter products of contaminant degradation. Specialized field equipment and technologies often are required to obtain representative samples of subsurface materials for use in column and microcosm studies. Usually more observation points are required for research studies than for other types of ground-water investigations, as are the demands for more stringent quality control.

Types of Ground-Water Investigations

Regional Investigations

Ground-water investigations can be carried out on a regional, local, or site-specific scale. The first, which may encompass hundreds or even thousands of square miles, is reconnaissance in nature, and is used to obtain an overall evaluation of a ground-water situation.

This broad-brush reconnaissance study can be the starting point for two general types of investigations. First, it can be carried out with the purpose of locating potential sources of contamination, or it may provide an understanding of the occurrence and availability of ground water on a regional scale. The underlying objectives are first, to determine if a problem exists, and second, if necessary, to ascertain prevalent hydrologic properties of earth materials, generalized flow directions of both major and minor aquifers, the primary sources and rates of recharge and discharge, the chemical quality of the aquifers and surface water, and the locations and yields of wells. These data can be useful in more detailed studies because they provide information on the geology and flow direction, both of which affect studies of smaller scale.

Local Investigations

A local investigation, which is conducted in the vicinity of a contaminated site, may cover a few tens or hundreds of square miles, and is used to determine local ground-water conditions. The purpose is to define, in greater detail, the geology, hydrology, and water quality in the area surrounding a specific site or sites of concern. This information is important in designing and carrying out more detailed site investigations.

Site Investigations

The goals of an investigation at a contaminated site are to ascertain, with considerable certainty, the nature and extent of contamination, its source or sources, and the relative movement of different contaminants and their degradation products. The end result is to provide information leading to an effective and cost-efficient remediation plan.

The site investigation is usually the most detailed, complex, costly, and, from the legal and restoration viewpoint, the most critical of the three types of ground-water studies. A site investigation must address a myriad of pertinent parameters affecting contaminant transport and transformation, including geology and hydrogeology, geochemical interactions, biotic and abiotic degradation processes, and the rate of movement of contaminants through the unsaturated and saturated zones. It also is important, when appropriate, to locate and determine the effect of phenomena influencing the movement of contaminant plumes such as nearby pumping wells, multiaquifer interactions, and local streams.

At the same time ground-water studies are being carried out there are usually auxiliary investigations. These may include tank inventories, toxicological evaluations, air pollution monitoring, manifest scrutiny, and manufacturing procedures, as well as other information gathering, all of which eventually combine in the development of a comprehensive report.

Organization and Development of the Investigation

Regardless of the complexity or detail of the investigation, a logical series of steps should be followed. Although each investigation is unique, these general rules are:

1. Establish objectives.
2. Prepare work plan
3. Data collection.

4. Data interpretation.
5. Develop conclusions.
6. Present results.

Establish Objectives

Establishing the major goal or goals of an investigation is paramount to a successful and cost-effective project. The exact goals should be clearly defined and agreed upon by all interested parties. They should be clearly expressed in writing and referred to often during the life of the study. Otherwise as the work progresses, there may be a tendency for the study to drift from the stated objectives, resulting in the collection of costly superfluous information, perhaps at the expense of required information.

The approach, time requirements, and funding can be vastly different between a regional reconnaissance evaluation and a site-investigation. The former, which deals with gross features, may only require a few days, while the latter, which necessitates minute detail, may demand years. In either case the time and resource requirements are dictated by the goals, and the success of the work is measured by how directly the investigation pursues those goals.

In one case the objective statement may be to "measure the water levels in a given township using existing wells." Another might be "evaluate the degradation rate of tetrachloroethylene at a specific spill site, define the plumes of the parent and degradation contaminants, and predict the location and concentrations of these contaminants after 10 years." In both of these examples the objective is clearly stated and the complexity is evident. In the first case, the caveat "using existing wells" states that the study, for whatever purpose, is very limited. Clearly the second set of goals is vastly more complicated and will undoubtedly require many observation points; a detailed knowledge of the site's soils, geochemistry, geology, and hydrogeology, sophisticated analytical capabilities; predictive models and the information necessary to drive them.

Once the general objective of the ground-water study is established, a number of secondary purposes must be considered. These involve the physical system and the chemical aspects. Secondary objectives include the following:

1. Determination of the thickness, soil characteristics, infiltration rate, and water-bearing properties of the unsaturated zone.

2. Determination of the geologic and hydrologic properties and dimensions of each geologic unit that potentially could be affected by ground-water contamination. This includes rock type, thickness of aquifers and confining units, their areal distribution, structural configuration, transmissivity, hydraulic conductivity, storativity, water levels, infiltration or leakage rate, and rate of evapotranspiration, if appropriate.

3. Determination of recharge and discharge areas, if appropriate.

4. Determination of the direction and rate of ground-water movement in potentially affected units.

5. Determination of the ground water and surface water relationships.

6. Determination of the background water-quality characteristics of potentially affected units.

7. Determination of potential sources of contamination and types of contaminants.

Prepare Work Plan

The preparation of the work plan or method of approach should be made in direct response to the stated goals, using existing data and information to the fullest extent possible. The investigative plan needs to be flexible in a practical way. For example, the position of all test wells, borings, and monitoring points cannot be determined in the office at the start of an investigation. Rather, these locations should be adjusted on the basis of information obtained as each hole is completed. In this way, one can maximize the data acquired from each drill site and more appropriately locate futures holes in order to develop a better understanding of the ground water and contamination situation at the site under study.

Similarly, the exact contaminants of target, appropriate analytical methods, detailed sampling techniques, and the required number of samples cannot be accurately estimated at the beginning of a project. These must be refined as data are collected and the statistics of those data interpreted.

The early development of a flexible plan of investigation occasionally may be required to include, at least in part, guidelines established by the Environmental Protection Agency, such as the Ground Water Technical Enforcement Guidance Document. State regulatory agencies may have even more stringent requirements. Also, in the case of Superfund and RCRA sites, the investigator probably will be required to work with or at least use data collected by consultants for the defendant.

In almost all cases, as the work progresses, it is necessary to adjust the work plan to one degree or another. In the event changes must be made, it is important that they do not cause the work to drift from the original objectives.

Even fairly simple ground-water investigations can result in large amounts of data, adjustment of the project approach, statistical evaluations, interpretations and conclusions, the preparation of graphics for presentations, and the final report. The work plan should contain provisions for dealing with data either by developing an automatic data processing program or selecting one from the software market. Also, if the project requires the use of mathematical models, data storage and retrieval systems should be developed in concert with these needs.

One section of the work plan should be dedicated to the health and safety of those actively participating in the investigation, as well as the general public. Health monitoring tests, performed before, during, and after the field work is completed, are necessarily predicated on estimates of the toxicity and concentration of contaminants at the site. Protective clothing and other safety considerations also must be based on these estimates until collected information becomes available. Access to the site should be limited to project personnel, particularly when drilling or other heavy equipment is in use.

Another section of the work plan should deal with chain-of-custody requirements when working at Superfund, RCRA, or other sites where litigation is involved. As discussed in EPA's Technical Enforcement Guidance Document, this section should include instructions concerning:

1. Sample labels to prevent misidentification of samples.
2. Sample seals to preserve the integrity of samples from the time they are collected until opened in the laboratory.
3. Field logbook to record information about each sample collected during the ground-water monitoring program.
4. Chain-of-custody record to document sample possession from time of collection to analysis.
5. Sample analysis request sheets, which serve as official communications to the laboratory of the particular analyses required for each sample and provide further evidence that the chain of custody is complete.
6. Laboratory logbook and analysis notebooks, which are maintained at the laboratory and record all pertinent information about the sample.

Data Collection

Existing Information. Data collection forms the basis for the entire investigation, consequently, time must be allocated and care exercised in addressing this part of the project. As mentioned above, all existing information should be collected, analyzed, and used to prepare a work plan before field activities are begun. The amount and types of data to be collected are dictated by the objectives of the study. Materials that should be collected, when available, include soil, geologic, topographic, county and state maps, geologic cross-sections, aerial photographs, satellite imagery, the location of all types of wells with discharge rates, well logs, climatological and stream discharge records, chemical data, and the location of potential sources of ground-water contamination.

Many of these data are readily available in the files and reports of local, state, and federal agencies. Personnel with these agencies also can be of great help because of their knowledge with the area and available literature. Examples include the U.S. Geological Survey, which has at least one office in each state, the state geological survey, and several state agencies that deal with water, such as the state water survey, water resources board, or a water commission. Other sources of information include the state or federal departments of agriculture, soil conservation, and the weather service, among others.

It often is useful to talk with long-term local residents, realizing that their information may be biased because of prejudices involving the cause of the investigation. Their historical knowledge often can assist in defining possible sources of contamination. For example, "there used to be a service station on that corner about 30 years ago," or "that company buried trash out in that field until after World War II." Often their memory is of events that are not available in the literature.

Climatological data are important because they indicate precipitation events and patterns, which influence surface runoff and ground-water recharge. Additionally, these data include temperature measurements that can be used for an evaluation of evapotranspiration, which, for shallow ground water can produce a significant effect on the water-table gradient, causing it to change in slope and direction, both seasonally and diurnally.

Soil types are related to the original rock from which they were derived. Consequently, soils maps can be used as an aid in geologic mapping, and they are valuable for estimating infiltration. Soil information also is necessary to evaluate the potential for movement of organic and inorganic compounds through the unsaturated zone.

Exceedingly useful tools, both in office and field study, are aerial photographs and satellite imagery. The latter should be examined first in an attempt to detect trends of lineaments, which may indicate the presence of faults and major joints or joint systems. These may reflect zones of high permeability that exert a strong influence on fluid movement from the land surface or through the subsurface. Satellite imagery also can be used to detect the presence of shallow ground water owing to the subtle tonal changes and differences in vegetation brought about by a higher moisture content. Rock types also may be evident on imagery.

Aerial photographs, particularly stereoscopic pairs, should be an essential ingredient of any hydrologic investigation. They are necessary to further refine the trends of lineaments, map rock units, determine the location of cultural features and land use, locate springs and seeps, as well as potential drilling sites, and detect possible sources of contamination. Topographic and state and county road maps also are useful for many of these purposes.

Geologic reports, maps, and cross sections provide details of the surface and subsurface, including the areal extent, thickness, composition, and structure of rock units. These sources of information should be supplemented, if possible, by an examination of the logs of wells and test holes. Depending on the detail of the logs, they may provide a clear insight into the complexities of the subsurface.

Logs of wells and test holes are essential in ground-water investigations. They provide first-hand information on subsurface strata, their thickness, and areal extent. They also may allow inferences as to relative permeability, well-construction details, and water-level depths.

Inorganic chemical data may be available from reports, but the most recent information is probably stored in local, state, and federal files. Concentrations of selected constituents, such as dissolved solids, specific conductance, chloride, and sulfate, may be plotted on base maps and used to estimate background quality and, perhaps, indicate areas of contamination.

Sources of information that report concentrations of organic compounds usually are scarce and should be questioned, particularly if they are old. It only has been within the last decade or so that organic compounds have become of concern in ground water. The cost of analysis is high, and much remains to be learned about appropriate sampling methods, storage, and interpretation. Consequently, when using existing data, investigators normally will need to rely on inorganic substances to detect contaminated ground-water sites. In some cases both organic and inorganic substances are present in a leachate. On the other hand, reliance on concentrations of inorganic constituents to evaluate contamination by organic compounds may not be appropriate, possible, or desirable.

Field Investigations. Several generalized methods have been available for a number of years to evaluate a possible or existing site relative to the potential for ground-water contamination. These rating techniques are valuable, in a qualitative sense, for the formulation of a detailed investigation. One of the most noted is the LeGrand (1983) system, which takes into account the hydraulic conductivity, sorption, thickness of the water-table aquifer, position and gradient of the water table, topography, and distance between a source of contamination and a well or receiving stream. The LeGrand system was modified by the U.S. Environmental Agency (1983) for the Surface Impoundment Assessment study.

Fenn and others (1975) formulated a water balance method to predict leachate generation at solid waste disposal sites. Gibb and others (1983) devised a technique to set priorities for existing sites relative to their threat to health. An environmental contamination ranking system was developed by the Michigan Department of Natural Resources (1983). On a larger scale DRASTIC, prepared by the National Water Well Association for EPA (1987), is a method to evaluate the potential for ground-water contamination based on the hydrogeologic setting. A methodology for the development of a ground-water management and aquifer protection plan was described by Pettyjohn (1989).

The field phase of a ground-water investigation is the most intensive and important part of the project. The data collected during this phase will determine its success. Some of the main factors affecting the quality of the field data include an understanding of the hydrogeology at the site, a knowledge of the types of contaminants involved and their behavior in the subsurface, the location and construction of monitoring wells, and how they are sampled and analyzed.

In order to detect and outline areas of contamination in the subsurface, an understanding of the movement of ground water is necessary. In soils the important parameters to quantify by field investigations include soil-moisture characteristic curves, soil texture, unsaturated hydraulic conductivity curves and preferential flow paths, such as fractures and macropores, and the spatial and temporal variability of these factors.

In the saturated zone it is important to determine the hydraulic properties of the aquifer including gradient, direction of flow and velocity, storativity, transmissivity, and hydraulic conductivity.

With respect to water levels and flow patterns, the factors that affect seasonal and temporal variations should be identified. Such factors include onsite and offsite pumping and recharge, tidal and stream stage fluctuations, construction, changes in land use, and waste disposal practices.

In addition to determining the gross hydraulic conductivity, its distribution also should be determined. Variations in hydraulic conductivity, both within and between strata, affect ground-water flow paths, including magnitude and direction, and must be identified in order to isolate major zones of contaminant migration.

If the aquifer is composed of a fractured media, the nature of the fractures is required for use in flow models. Although this information can be very difficult to obtain, it can be helpful to collect information describing fracture density, location, orientation, roughness, and the degree to which they are connected.

A number of techniques are available to measure the hydraulic properties of aquifers. A few of the techniques include the following:

1. Aquifer tests are performed by pumping from one well and observing the resulting drawdown in nearby wells. These analyses can be used to determine an aquifers coefficients of storativity and transmissivity.
2. Slug tests are conducted by suddenly removing or adding a known volume of water from a well and observing the return of the water level to its original location. Slug tests are used to determine hydraulic conductivity.
3. Flow-net analyses, both horizontal and vertical, also permit an evaluation of hydraulic parameters and flow directions, and aid in the understanding of the role played by strata of different permeability.
4. Tracer tests can be used to determine if two locations are hydraulically connected, measure flow velocities, and determine the variability of hydraulic conductivity within an aquifer system.
5. Borehole dilution tests can be used to determine the hydraulic conductivity in a single well by introducing a tracer and measuring the dilution with time caused by the inflow of water into the well that is brought about by the natural hydraulic gradient in the vicinity of the well.
6. Rock cores taken during the drilling of wells and test holes can be analyzed in the laboratory to determine a number of physical and chemical properties, including porosity, hydraulic conductivity, and mineralogy. Care must be used in an evaluation of hydraulic parameters determined by laboratory analyses of unconsolidated materials.
7. Surface and borehole geophysics, aerial photography, and imagery are particularly helpful in working with fractured media.

After the site has been described in terms of ground-water movement, the work plan can be adjusted to sample for contaminants in the unsaturated and saturated zones. Nested lysimeters can be used to detect contaminants in the unsaturated zone; however, great care must be taken to assure that the collected samples are representative and not affected by sorption and volatilization. The placement of nested piezometers in closely spaced, separate boreholes of different depths generally is preferred to determine vertical head differences and the vertical movement of contaminants, while monitoring wells with appropriately located screens are used to determine the lateral movement of contaminants in the saturated zone.

As discussed above, an understanding of the variability or distribution of hydraulic conductivity, in both the vertical and horizontal dimension, allows one to isolate the major zones of water transmission and, therefore, to select the proper lengths and depths for well screens. This follows for offsite, upgradient, and downgradient observation points.

The length and position of well screens also must be predicated on the nature of the contaminant. For example, it the contaminants are miscible with the liquid phase, it may be possible to use only one well per sampling point. It also may be possible to use only one well if the transmissive zone is very thin. If the contaminants are immiscible with the liquid phase (sinkers or floaters), the well screens must be located appropriately.

In carrying out a ground-water investigation it is not uncommon for at least part of the chemical species of concern to be dictated by state or federal regulations, such as the RCRA list of priority pollutants. Beyond this one must be aware of contaminant transformation phenomena in the design and implementation of a ground-water sampling program. For example, when selecting proper contaminant targets it is imperative to realize that the original species may have been reduced in concentration, altered, or eliminated by chemical, physical, or biological processes taking place in the subsurface environment. Aerobic and anaerobic biological degradation, and hydrolysis and redox reactions are among these processes. The sampling protocol also should be influenced by alterations in the transport of contaminants caused by immiscible compounds, sorption-desorption phenomena, and the facilitated transport of hydrophobic compounds.

Data Interpretation

Data interpretation should begin with the development of the work plan. Today's widespread availability and use of computers allow the application of data processing to the results of almost all investigations and software exists for a wide variety of data handling requirements. To the extent possible, the amounts and types of data should be anticipated early in the project and provisions made for the continuous input of collected information as the work progresses. Also, the quality assurance and quality control program should be built into the data handling system so that the quality of the data can be continuously monitored.

If predictive models are required at some point in the investigation, or later in the development of an aquifer remediation project, they should be formulated or selected from existing models as early as possible so that requirements for acquisition of the appropriate data can be built into the work plan. Steps also should be taken for model calibration and validation as the investigation proceeds.

Even at a moderately sized site, a ground-water investigation of limited scope can result in the collection of a great deal of information. The amount of time saved and the amount of frustration avoided during data interpretation is directly proportional to the skill with which one anticipates (1) the types and amounts of data collected; (2) the calculations required to determine contaminant transformation process rates, support conclusions, and make projections; (3) the correlations required to prove cause and effect, define relationships, and determine reaction coefficients; and (4) prepare the graphic displays needed for reports and presentations.

Develop Conclusions

In a very real sense the development of conclusions, like preparing for the interpretation of data, should be done in the early stages of the project by establishing hypotheses. These hypotheses must be proposed in direct response to the objectives of the investigation, then, as in hypothesis testing in statistics, the project designed around their acceptance or rejection. If done correctly, this approach can play a significant role in assuring that the project design is an efficient response to the project goals, and that the collection of extraneous information is kept to a minimum.

To carry this point further, assume that gasoline fumes are detected in the basement of a small house. A service station is located immediately to the east at a slightly higher elevation. There is another service station about 200 feet south of the first, across a street. The goal of an investigation would be to determine the source of gasoline so that negligence could be proven. If one assumed that the shallow water table followed the surface topography, the first hypothesis would be that the gasoline originated from the closest, upgradient buried tanks. After drilling only three shallow wells, water-level data might prove that the ground water was moving due west from the closest station and the first hypothesis could be accepted.

On the other hand, the water-level data could show that the gradient did not follow the lay of the land but was about 30 degrees west of north. In this case the first hypothesis must be rejected with the conclusion now being that the second service station is at fault. At this point the investigation might be ended or additional proof provided by drilling wells to delineate the plume and show that no other sources existed.

A more complicated example might involve the need to define the plume of contamination at a Superfund site so that a remediation plan could be developed. The goal would be to locate the plume horizontally, as well as vertically, and provide concentration isograms. If the parent contaminant were trichloroethylene, the hypothesis must be made that biodegradation is taking place and that the well placements, sampling, and analytical procedures must be designed to also locate dichloroethylene and vinyl chloride.

Many of today's ground-water contamination problems are extremely complex, particularly those associated with hazardous waste sites. It is very important, therefore, that conclusions be based on the collective wisdom and experience of interdisciplinary teams to the fullest extent possible.

Present Results

All investigations usually result in a report and commonly other types of presentations as well. Their style and content are determined by the type of study and can vary in as many ways as the investigations themselves. However, some general traits can be suggested.

Those studies designed to "Establish Background" and those for "Monitoring" cause-and-effect relationships should consist predominantly of field data appropriately grouped and tabulated for easy access. Reports prepared for use in litigation are usually brief with only the essentials of the study highlighted along with the essence of the findings—most often in proof or disproof of a legal argument. "Site Characterization" reports generally are more complete and detailed than other reports because they generally serve as the basis of other activities, such as the design and implementation of a remedial action plan or a complex and costly compliance monitoring system.

Examples of Ground-Water Investigations

Regional Examples

Regional investigations are conducted for many different purposes. One type is to detect potential sources and locations of ground-water contamination. Another type of exceedingly broad scope includes library searches. Examples entail an early EPA effort to evaluate ground-water contamination throughout the United States (van der Leeden and others, 1975, Miller and Hackenberry, 1977, Scalf and others, 1973, Miller and others, 1974, and Fuhriman and Barton, 1971). The reports are useful for obtaining a general appreciation of the major sources and magnitude of contamination over a regionally extensive area.

In 1980, individuals in EPA Region VII became aware of what appeared to be a large number of wells that contained excessive concentrations of nitrate. Suspecting a widespread problem, a regional reconnaissance investigation was initiated. The general approach consisted of a literature search, a meeting in each state with regulatory and health personnel, an evaluation of existing data, and an interpretation of all of the input values.

The fundamental principle guiding this study was the fact that abnormal concentrations of nitrate can arise in a variety of ways, both from natural and human-made sources or activities. The degradation may encompass a large area if it results from the over-application of fertilizer and irrigation water on a coarse textured soil, from land treatment of waste waters, or from a change in land use, such as converting grasslands to irrigated plots. On the other hand, it may be a local problem affecting only a single well if the contamination is the result of animal feedlots, municipal and industrial waste treatment facilities, or improper well construction or maintenance.

Most of the data base for this study was obtained from STORET. First, nitrate concentrations in well waters were placed in a separate computer file. Two maps were generated from the file, the first showing the density of wells that had been sampled for nitrate, and the second showing the density of wells that exceeded 10 mg/L of nitrate (fig. 6-1). These maps indicated the areas of the most significant nitrate problems. In turn, the nitrate distribution maps were compared to geologic maps, which allowed some general identification of the physical system that was or appeared to be impacted (fig. 6-2).

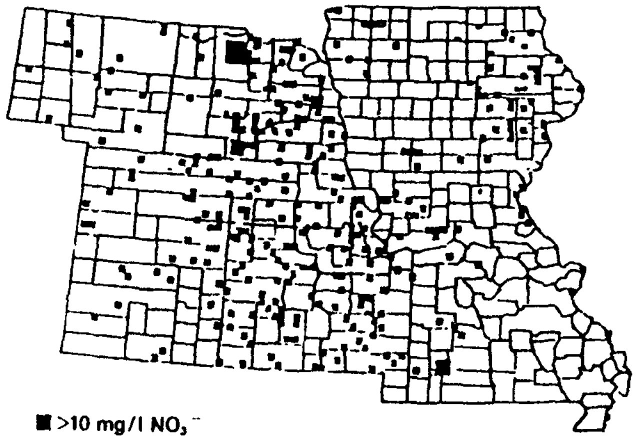

Figure 6-1. Location of Wells with Nitrate Exceeding 10mg/L in Region VII

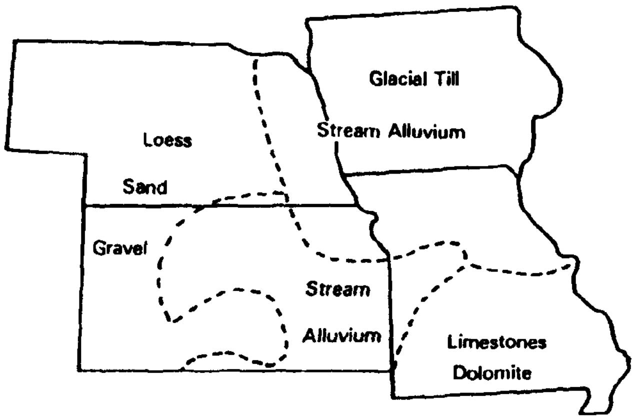

Figure 6-2. Generalized Rock Types with High Nitrate Concentrations in Region VII

Iowa, eastern Nebraska, northeastern Kansas, and the northern third of Missouri are characterized by glacial till interbedded with local deposits of outwash. Throughout the area are extensive deposits of alluvium. Many of the aquifers are shallow and wells are commonly dug, bored, or jetted. This area contained the greatest number of domestic wells with high nitrate concentrations. It also contained the greatest number of municipal wells that exceeded the nitrate Maximum Contaminant Level (MCL). The cause of contamination in the shallow domestic wells was suspected to be poor well construction and maintenance, but this was possibly not the case for many of the generally deeper municipal wells, where the origin appeared to be from naturally occurring sources in the glacial till.

Most of Nebraska and western Kansas are mantled by sand, gravel, and silt, which allow rapid infiltration. The water table is relatively shallow. The irrigated part of this region, particularly adjacent to the Platte River and in areas of Holt County, NB, contained the greatest regional nitrate concentrations in the four state area. This was brought about by the excessive application of fertilizers and irrigation waters in this very permeable area.

The remaining area in Kansas and an adjacent part of Missouri is underlain by sedimentary rocks across which flow many streams and rivers with extensive flood plains. Most of the contaminated wells tapped alluvial deposits. The primary cause of high nitrate in domestic wells was suspected to be poor well construction and maintenance, or poor siting with respect to feedlots, barnyards, and septic tanks.

The southern part of Missouri is represented by carbonate rocks containing solution openings. Aquifers in these rocks are especially susceptible to contamination and the contaminants can be transmitted great distances with practically no change in chemistry other than dilution. The carbonate terrain is not easily managable nor is monitoring a simple technique because of the vast number of possible entry sites whereby contaminants can enter the subsurface.

The STORET file also was used to generate a number of graphs of nitrate concentration versus time for all of the wells that were represented by multiple samples. The graphs clearly showed that the nitrate concentration in the majority of wells ranged within wide limits from one sampling period to the next, suggesting leaching of nitrate during rainy periods from the unsaturated zone.

The state seminars were exceedingly useful because the personnel representing a number of both state and federal agencies had a good working knowledge of the geology, water quality, and land-use activities of their respective states.

Although the study extended over several months, the actual time expended amounted to only a few days. The conclusions, for the most part, were straightforward and, in some cases, pointed out avenues for improvement in sample collection and data storage/ access. The major conclusions are as follows:

1. High levels of nitrate in ground water appeared to be randomly distributed throughout the region.

2. The most common cause of high nitrate concentration in wells was the result of inadequate well construction, maintenance, and siting. Adequate well construction codes could solve this problem. Dug wells, those improperly sealed, and wells that lie within an obvious source of contamination, such as a pig lot, should probably be abandoned and plugged.

3. In areas of extensive irrigation where excess water was applied to coarse textured soils, the nitrate concentration in ground water appeared to be increasing.

4. In the western part of the region, changes in land use, particularly the cultivation or irrigation of grasslands, had resulted in leaching of substantial amounts of naturally occurring nitrate from the unsaturated zone.

5. The population that was consuming high-nitrate water supplies was small, accounting for less than 2 per cent of the population.

6. There had been no more than two reported cases of methemoglobinemia in the entire Region within the preceeding 15 years despite the apparent increase in nitrate concentration in ground-water supplies. This implied a limited health hazard.

7. State agency personnel were convinced that they did not have significant nitrate-related health problems

8. Many of the wells used in state and federal monitoring networks are of questionable value because little or nothing is known about their construction.

9. The volume of chemical data presently in the files of most of the state agencies within the region is not adequately represented in the STORET data system.

This cursory examination provided only a general impression of the occurrence, source, and cause of abnormal nitrate concentrations in ground water in the Region. Nonetheless, it furnished a base for planning local or site investigations, was prepared quickly, and did not require field work or extensive data collection.

As mentioned previously, the source of excessive nitrate in many municipal wells could not be readily explained. There could be multiple sources related to naturally occurring high nitrate concentrations in the unsaturated zone or the glacial till, to contamination, or to poor well constructioin. Definitive answers would require more detailed local or site studies.

The overall effect of changing from grazing land to irrigated agriculture, in view of the great mass of nitrate in the unsaturated zone, warrants additional local investigation. Although the concentration of nitrate in underlying ground water would increase following irrigation, it is likely that some control on the rate of leaching could be implemented by limiting the amount of water applied to the fields.

The obvious relationship between the application of excessive amounts of fertilizer and water on a coarse textured, as was the case in Nebraska, shows the need for experimental work on irrigation techniques in order to reduce the loading. Also implied is the necessity for the development of educational materials and seminars to offer means whereby irrigators can reduce water, pesticide, and fertilizer applications, and yet maintain a high yield.

Local Example

Local investigations can be as varied in scope and areal extent as regional evaluations and the difference between the two is relative. For example, one might desire to obtain some knowledge on the hydrogeology of an area encompassing a few tens or several hundred square miles in order to evaluate the effect of oil-field brine production and disposal. Examples of this scope include Kaufmann (1978) and Oklahoma Water Resources Board (1975). The other extreme may center around a single contaminated well. In this case the local investigation would most likely focus on the area influenced by the cone of depression, the size of which depends of the geology, hydraulic properties, and well discharge.

Consider an area in the Great Plains where a number of small municipalities have reported that some of their wells tend to increase in chloride content over a period of months to years. The increase in a few wells has been sufficient to cause abandonment of one or more wells in the field. Additionally, a number of wells when drilled yielded brackish or salty water necessitating additional drilling elsewhere. This is an expensive process that strains the operating budget of a small community.

In this case, a local investigation covered an area of about 576 mi^2. A review of files and reports and discussions with municipal officials and state and federal regulatory agencies indicated that the entire area had produced oil and gas for more than 30 years. Inadequate brine disposal appeared to be the most likely cause of the chloride problem.

During the initial stage of the investigation, all files dealing with the quality of municipal well water were examined. This task was followed by a review of the geology, which included a assessment of all existing maps, cross sections, and well logs, both lithologic and geophysical.

The chemical data clearly showed that the chloride content in some wells increased with time, although not linearly. The geologic phase of the study showed that the rocks consist largely of interbedded layers of shale and sandstone and that the sandstone deposits, which serve as the major aquifers, are lenticular and range from 12 to about 100 feet in thickness. The sandstones are fine-grained and cemented to some degree and, as a result, each unit will not yield a large supply. Resultingly, all sandstone strata are screened.

Trending north-south through the east-central part of the area is an anticline (fig. 6-3) that causes the rocks to dip about 50 feet per miles either to the east or west of the strike of the structure (fig. 6-4). This means that a particular sandstone will lie at greater depths with increasing distances from the axis of the anticline.

In this example, the subsurface geology was examined by an evaluation of geophysical and geologists logs of wells and test holes, including oil and gas wells and tests. As shown in Figure 6-4, interpretation of the logs, in the form of a geologic cross section, brings to light an abundance of interesting facts. The municipal wells range in depth from 400 to 900 feet, but greater depth does not necessarily indicate a larger yield nor does depth imply a particular chemical quality. The difference in well depth and yield is related to the thickness and permeability of the sandstone units encountered within the well bore. Secondly, the volume of the sandstone components ranges widely, but the thinnest and most discontinuous units increase in abundance westward. More importantly, the mineral content of the ground

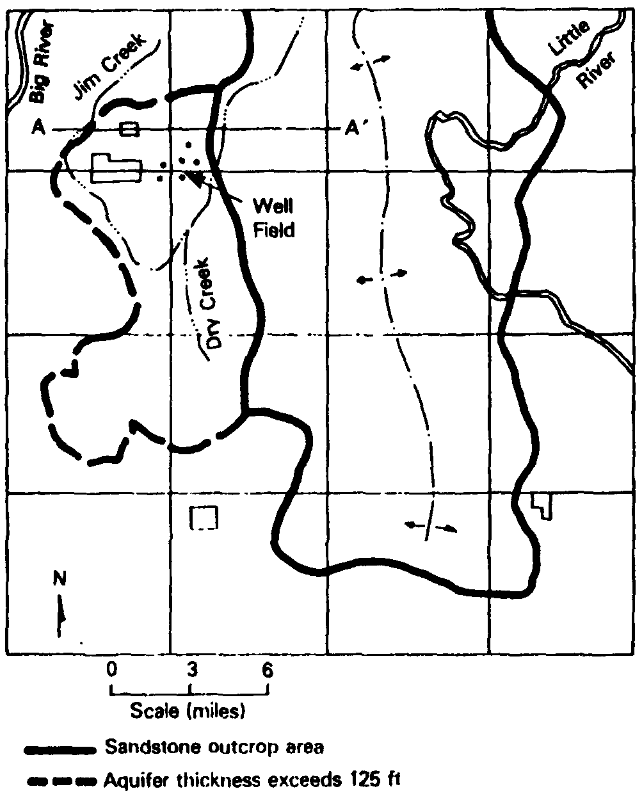

Figure 6-3. Generalized Geologic Map of a Local Investigation

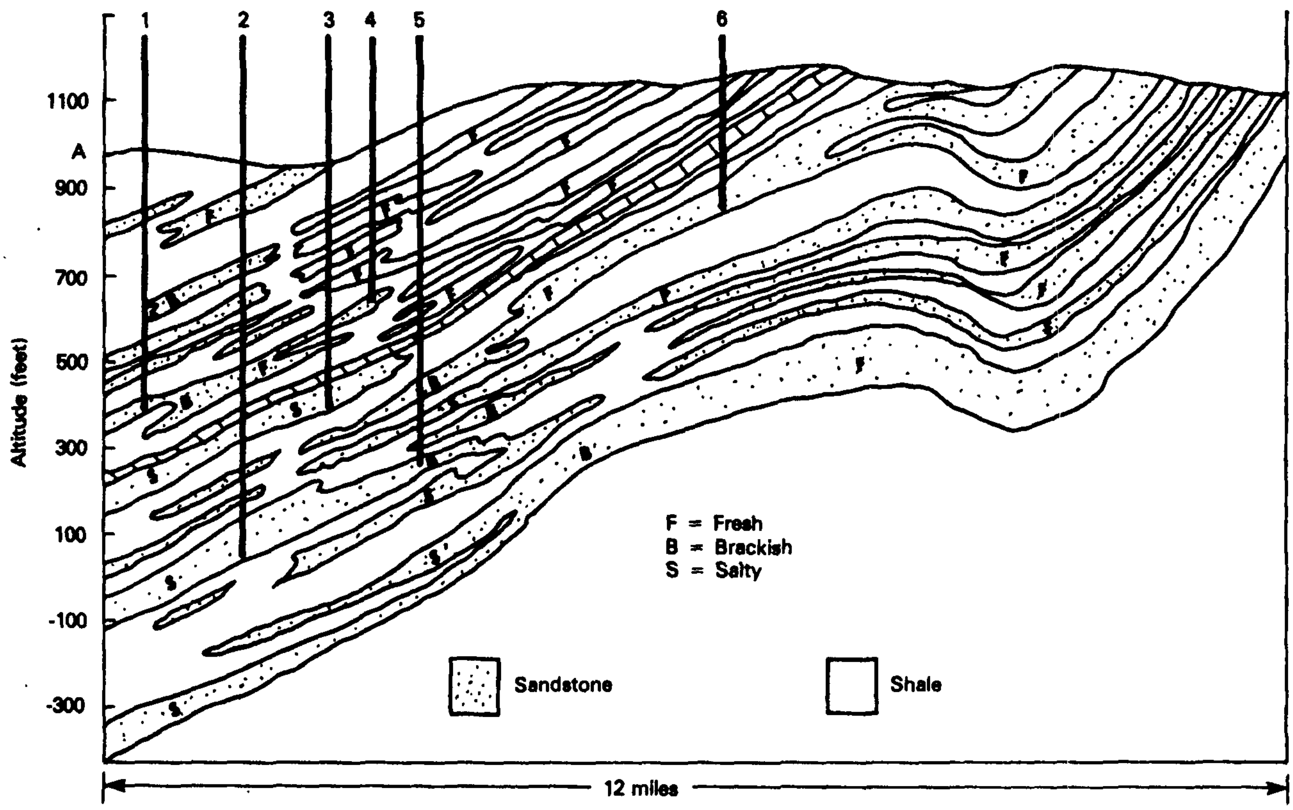

Figure 6-4. Geologic Cross-Section Showing Downdip Change in Water Quality

water, which can be determined from geophysical logs, increases down the dip of the sandstone, from fresh in the outcrop area, to brackish, and finally to salt water (fig. 6-4). Notice also that brackish and saline water lie at increasingly shallower depths to the west of the outcrop area.

The position and depth of a few municipal wells and test holes are also shown on the cross section. Well 1 would be expected to have a small yield of brackish water. Well 2 is an abandoned test hole that penetrated a thick saline zone and a thick brackish water zone. In the case of Well 3, the freshwater derived from the thin, shallower sandstones is sufficient to dilute water derived from the more mineralized zones. On the other hand, as the artesian pressure in the shallow sandstones decreases with pumping and time, an increasing amount of the well yield might be derived from the deeper brackish layer, causing the quality to deteriorate.

The major conclusion derived from this study is that the most readily apparent source of high chloride content in municipal wells, that is, inadequate oil-field brine disposal, is not the culprit. Rather all of the problems are related to natural conditions in the subsurface, brought about by the downdip increase in the dissolved solids content as freshwater grades into brackish and eventually into saline water. Deterioration of municipal well water quality is related to the different zones penetrated by the well and to a decrease in artesian pressure in freshwater zones brought about by pumping. The latter allows updip migration of brackish or saline water. Furthermore, the migration of mineralized water could occur through the well bore or by lateral or vertical leakage from one aquifer to another, which again is the result of a pressure decline in the freshwater zones. The problem could be diminished by constructing future wells eastward toward the axis of the anticline, limiting them to those areas either within the outcrop or where the thickness of the freshwater aquifers comprise a total thickness that exceeds 125 feet (fig. 6-3).

Site Example

Site investigations are ordinarily complex, detailed, and expensive. Furthermore, the results and interpretations are likely to be thoroughly questioned in meetings, interrogatories, and in court, because the expenditure of large sums of money may be at stake. The investigator must exercise extreme care in data collection and interpretation. The early development of a flexible plan of investigation is essential and it must be based, at least in part, on guidelines established by the EPA, such as the Ground-Water Monitoring Technical Enforcement Guidance Document. State regulatory agencies may have even more stringent requirements. In the case of Superfund and RCRA sites, the regulatory investigator probably will be required to work with or at least use data collected by consultants for the defendant. In some cases, the defendant conducts and pays for the entire investigation; regulatory personnel only modify the work plan so that it meets established guidelines. There are two points to consider in these situations. First, the consultant is hired by the defendant and should act in his best interest. This means that his interpretations may be biased toward his client and concepts detrimental to the client are not likely to be freely given. Second, even though the regulatory investigator and the consultant, to some degree, are adversaries, this does not mean that the consultant is dishonest, ignorant, or that his ideas are incorrect. It must always be remembered that the entire purpose of the investigation is to determine, insofar as possible, what has or is occurring so that effective and efficient corrective action can be undertaken. In the long run cooperation leads to success.

As an example of a ground-water quality site investigation, consider a rather small refinery that has been in existence for several decades. For some regulatory reason an examination of the site is required. The facility, which has not been in operation for several years, includes an area of about 245 acres. The geology consists of alternating layers of sandstone and shale that dip slightly to the west; the upper 20 to 30 feet of the rocks are weathered.

Potential sources of ground-water contamination include wastewater treatment ponds, a land treatment unit, a surface runoff collection pond, and a considerable number of crude and product storage tanks. Line sources of potential contaminants include unimproved roads, railroad lines, and a small ephemeral stream that carries surface runoff from the plant property to a holding pond.

After considering the topography and potential sources of contamination, the location of 11 test borings was established. The purpose of the holes was to determine the subsurface geologic conditions underlying the site. Following completion, the holes were geophysically logged and then plugged to the surface with a bentonite and cement slurry. The borehole data were used to determine drilling sites for 20 observation wells, in order to ascertain the quality of the ground water, to establish the depth to water, and to determine the hydraulic gradient. Eight of the observation wells were constructed so that they could be used later as a part of the monitoring system. Two of the wells tapped the weathered shale, their purpose being to monitor the water table, evaluate the relation between precipitation and recharge, and ascertain the potential fluctuation of water quality in the weathered material in order to determine if it might serve as a pathway for contaminant migration from the surface to the shallowest aquifer. (From a technical perspective, the weathered shale and sandstone is not an aquifer, but from a regulatory point of view it could be considered a medium into which a release could occur and, therefore, would fall under RCRA guidelines.)

Regulations required that the uppermost aquifer be monitored, which in this case was a relatively thin, saturated sandstone. After the initial investigative information was available, all of the findings were used to design a ground-water monitoring system. This plan called for an additional 12 monitoring wells.

Graphics based on all of the drilling information (geologic and geophysical logs) included several geologic cross sections (fig. 6-5) and maps showing the thickness of shale overlying the aquifer (fig. 6-6), thickness of the aquifer, and the hydraulic gradient (fig. 6-7). The major purpose of the first map was to show the degree of natural protection that the shale provided to the aquifer relative to infiltration from the surface. The aquifer thickness map was needed for the design of monitoring wells. The water-level gradient map was necessary to estimate ground-water velocity and flow direction. During the drilling phases, cores of the aquifer and the overlying shale were obtained for laboratory analyses of hydraulic conductivity, porosity, specific yield, grain size, mineralogy, and general description. Aquifer tests were conducted on two of the wells.

The cross sections and maps indicate that the sandstone dips gently eastward and nearly crops out in a narrow band along the western margin of the facility. Elsewhere, owing to the change in topography and the dip of the aquifer, the sandstone is overlain by 25 feet or more of shale; throughout nearly all of the site the shale exceeds 50 feet in thickness. Consequently, only one small part of the aquifer, its outcrop and recharge area, is readily subject to contamination.

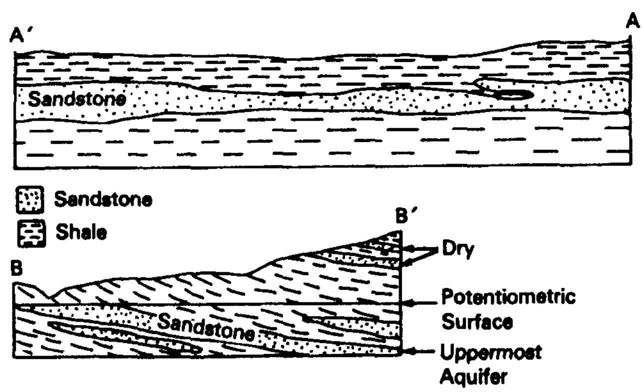

Figure 6-5. Geologic Cross-Section for the Site Investigation

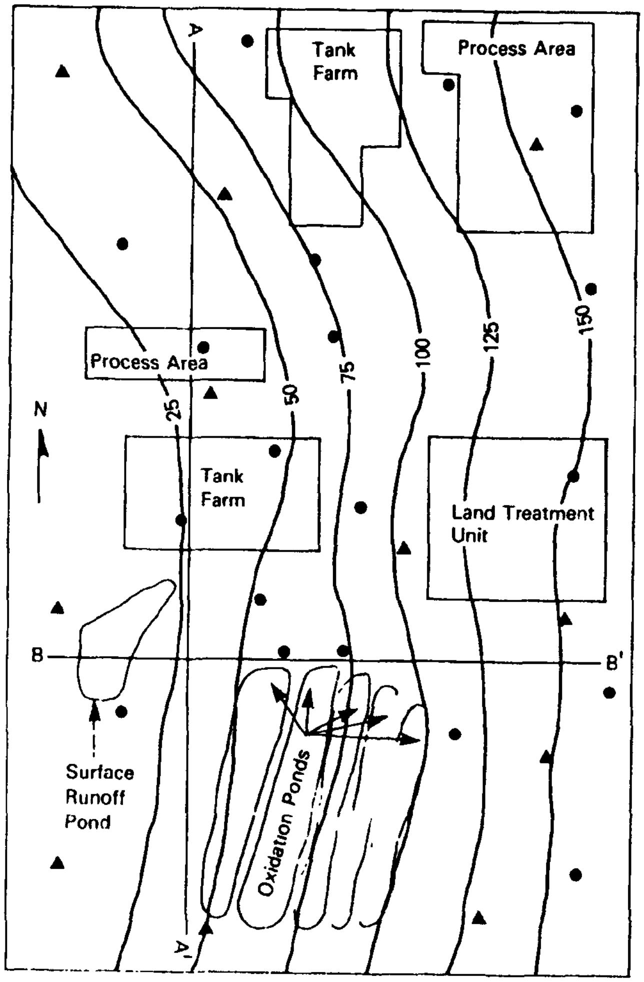

Figure 6-6. Map Showing Thickness of Shale Overlying the Uppermost Aquifer

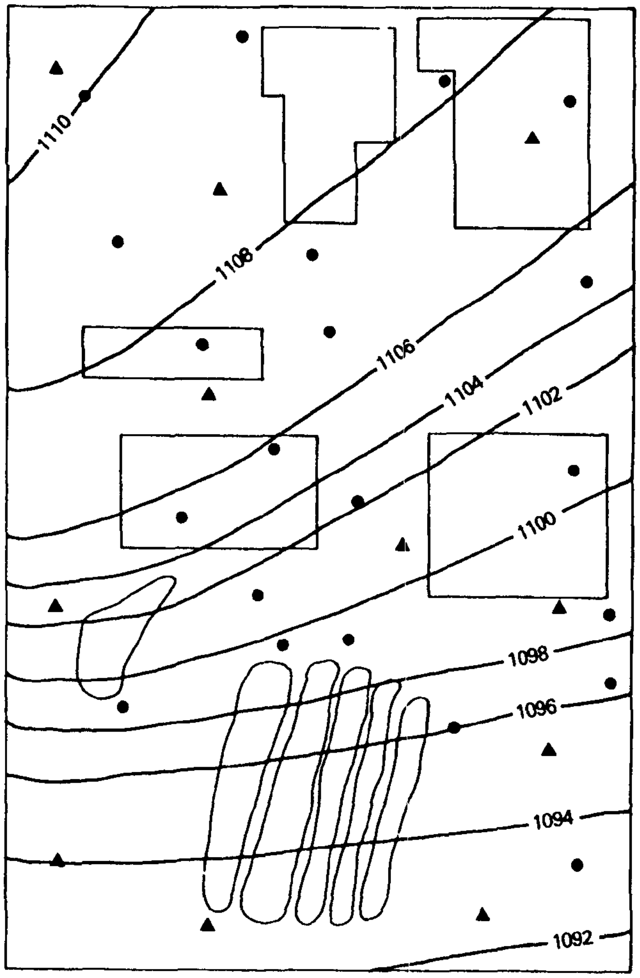

Figure 6-7. Potentiometric Surface of the Uppermost Aquifer

The water-level map indicates that the hydraulic gradient is not downdip but rather about 55 degrees from it. It is controlled by the topography off site. The average gradient is about 0.004 ft/ft, but from one place to another it differs to some extent, reflecting changes in aquifer thickness and hydraulic conductivity.

The topographic map indicates that surface runoff from the entire facility is funneled down to a detention pond. The pond and the lower part of the drainage way lie in the vicinity of the aquifer's recharge or outcrop area.

Logs of the drill holes list specific depths in six of the holes in which highly viscous hydrocarbons were present. All were reported in the unsaturated zone at depths of 2 to 9 feet with thicknesses ranging from a half inch to nearly a foot. At these locations the shale overlying the aquifer exceeded 55 feet in thickness.

Chemical analyses of water from the observation wells indicated, with one exception, that the quality was within background concentrations and no organic compounds were present. The exception was an observation well near the surface runoff retention pond.

Evaluation of all of the data indicated two potential problems—hydrocarbons in the unsaturated zone and ground-water contamination in the vicinity of the surface runoff detention pond. Since the plant had been in operation more than 50 years, the hydrocarbons had migrated from the surface into the weathered shale no more than 9 feet, and there was a minimum of at least 45 feet of tight, unfractured shale between the hydrocarbons and the shallowest aquifer, it did not appear that the soil contamination would present a hazard to ground water.

The existence of contaminated ground water, however, was a problem that needed to be addressed even though the sandstone aquifer is untapped and is never likely to serve as a source of supply. Four additional monitoring wells were installed downgradient in order to determine the size of the plume and its concentration. Corrective action called for removal of sediment and sludge from the pond, backfilling with clean material, a cap, and pumping to capture the plume. The contaminated water was treated on site with existing facilities.

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Chapter 7

GROUND-WATER RESTORATION

Introduction

Prevention of ground-water contamination is far more logical, simple, and cost-effective than attempting to correct a problem—a problem that may have been in existence for years. A great deal of time, effort, and money are presently being expended to develop remedial measures to counteract the effects of contaminated aquifers and public water supplies. These include traditional as well as innovative construction techniques, water management, and research initiatives.

Several options or combinations of options are available to restore a contaminated aquifer: (1) provide inground treatment/containment, (2) provide aboveground treatment, (3) remove or isolate the source of contamination, (4) abandon the source of supply, or (5) ignore the problem. Generally, several techniques are coupled in order to achieve the desired results.

Restoration of contaminated aquifers to former background or near background conditions or to contain contaminated ground water in certain locations is generally accomplished through one of two overall approaches. One approach involves natural or induced in situ treatment, while the other approach uses engineered systems to contain the contaminated ground water. In the latter case pumping wells or engineered structures are installed in order to develop hydraulic gradients that cause the contaminated water to remain in a specified, general location from which it may be removed for later treatment.

Regardless of the restoration approach, any source or sources that continue to contaminate the ground water should be removed, isolated, or treated. Treatment or removal of an existing contamination source eventually may result in restoration of ground-water quality through natural processes. In other situations, contaminated ground water is removed from the aquifer by pumping or is allowed to discharge to a stream in which the flow is sufficient to dilute the contaminant to nondetectable concentrations. Natural replacement of the ground water is relied upon to eventually restore the quality of the water in the aquifer. Typically the natural restoration processes require many years or perhaps even decades for completion. As a result, ground-water restoration commonly requires a combination of approaches that involve ground-water removal and treatment or, if necessary, induced in situ treatment coupled with source control (removal, isolation, treatment). Site-specific conditions, properly defined and understood, provide the ground-water investigator with the basic information needed for the determination of a viable approach and for selecting and designing a cost-effective restoration scheme.

This chapter provides an overview of aquifer restoration technologies utilizing techniques derived from interrelated disciplines of geology, hydrology, geochemistry, engineering, construction, biology, and agronomy. The major emphasis of the chapter is on ground-water pumping systems and in situ biological treatment for organic contaminants, which are found at almost all hazardous waste sites. Many of the technologies have been developed by demonstration and research in conjunction with remedial activities in the Superfund program. Detailed information on selected techniques can be obtained from the references.

Contaminant Mobility

The design of a ground-water restoration program is complicated by the fact that all contaminants do not behave in the same manner. Although discussed previously, it is important to briefly redescribe the significance of contaminant mobility in developing and designing a ground-water restoration program.

The movement of most ground-water contaminants is controlled by gravity, the permeability and wetness of the geological materials, and the miscible character of the contaminants in ground water. When a material, particularly a hydrocarbon, is released to the soil, capillary attraction and gravity actively draw it into the soil. As the main body of material moves downward into the more moist regions of the soil, capillary forces become less important as the contaminants move through the more favorable channels by displacing air.

When the contaminants reach the water table, those less dense than water tend to spread laterally along the air-water interface or capillary fringe, while the heavier ones continue to move downward in the saturated zone. In both cases, the contaminants tend to migrate in the direction of ground-water flow. In unusual circumstances very dense contaminants may be more affected by gravity than by advective flow and move in directions other than that of the ground water.

The amount of a contaminant that reaches the water table depends on the quantity involved, the characteristics of the contaminant, the chemical and biological properties of the unsaturated zone, precipitation (ground-water recharge), and the physical and chemical characteristics of the earth materials. In general, the more permeable the earth material, the greater the quantity of contaminant that is likely to reach the ground water. The entire amount of a contaminant may be temporarily immobilized in the unsaturated zone so that it only migrates downward after rainfall events, becoming a continual or long-term contamination source. Material so immobilized in the unsaturated zone may remain there unless physically, chemically, or biologically removed.

A hydrocarbon liquid phase, for example, generally is considered to be immiscible with both water and air. Residual hydrocarbons can occupy from 15 to 40 percent of the available pore space. However, it is important to realize that various components of the hydrocarbon may slowly volatilize into the vapor phase and then dissolve into the liquid phase. A halo of dissolved components of the hydrocarbon precedes the immiscible phase, some of which becomes trapped in the pore spaces and is left behind as isolated masses. Even when the so-called residual phase is entirely immobile, ground water coming into contact with the trapped material leaches soluble components and continues to contaminate ground water.

Interaction of the contaminant and the aquifer materials is another consideration in the evaluation of contaminant mobility. Some contaminants tend to partition between the liquid, solid, and vapor phases in amounts dictated by the characteristics of each contaminant, the nature of the aquifer material, particularly the amount of organic carbon, and other geochemical parameters. For many contaminants, these associations are not fixed but can be completely reversible. In addition, these compounds may move freely from one phase to another, depending upon their concentration in each phase. The processes of ion-exchange and sorption, chemical precipitation, and biotransformation all result in retardation or transformation of the contaminants. Ground water can become contaminated as freshwater moves through or past the aquifer material where contaminants are attached, or as infiltrating water moves through the unsaturated zone, which contains contaminants in the vapor phase. The subsurface transport of hydrophobic compounds is an active field of research.

Highly soluble contaminants, such as salts, some metal species, and nitrates, have little affinity for sorption to the solid phase. For aquifer restoration purposes, these contaminants can be considered to move essentially in the same direction and velocity as the ground water and are ideal candidates for pump-and-treat technology.

Site Characterization

In most restoration schemes, all too often the physical features of the subsurface are largely ignored and little understood, and most of the effort is involved with the design and construction of engineering structures. The important point to consider, however, is that the physical features of the subsurface, that is, the distribution of permeability and porosity, and the resulting hydrogeologic characteristics control the movement and storage of fluids in the subsurface.

Ground-water restoration activities require dedication of sufficient resources to collect and understand site conditions. An adequate amount of field data must be collected to provide a detailed understanding of the geology, hydrology, and geochemistry of the site, as well as the types of contaminants to be removed, their concentrations, and distribution. The literature should be reviewed to determine, to the fullest extent possible, the contaminants characteristics of sorption, volatilization, partitioning, and ability to be degraded. Finally, laboratory investigations, including treatability studies, development of sorption isotherms, and column and microcosm examinations to determine contaminant transport and transformation parameters, assist in developing a full understanding of the site conditions, and potential alternatives for ground-water remediation.

Many ground-water texts and reports, particularly the older ones, show ground-water flow nets to be homogeneous in both the horizontal and vertical dimensions—at least on a regional scale. In reality such depictions are rare and the actual water movement is much more complicated. Flow lines drawn on a water-table map, for example, imply that the fluids are moving directly downgradient when, in fact, the flow actually follows curvilinear paths (see Chapter 4). All too often significant amounts of the flow may be through limited parts of the aquifer, both horizontally and vertically. This could result from the spatial variability of permeability for water, or it could result from density or other considerations for contaminants. In other words, neither the bulk of the water flow nor the distribution of the contaminants can be assumed as homogeneous.

Figure 7-1 is the map of a contaminated waste disposal site that shows the location of a number of monitoring wells and the altitude of the water surface in them. Notice that there is as much as 100 feet of difference in head in wells that are relatively close. The reason for this difference is well depth, with the deeper wells having the greatest depth to water. Figure 7-2 is a water-level map of the same area; contours were based on shallow wells of nearly the same depth and screen length. Flow lines depict the general direction of ground-water movement. Figure 7-3 is a hydrologic cross section, that is, a vertical flow net, constructed along the line A-A'. Notice in this example that in the upper 50 feet or so the ground water is flowing across different geologic units with little loss in head. This indicates that secondary permeability (fractures), rather than the primary permeability of the various geologic units, is the major control on ground-water flow. In the lower part of the cross section the water-level contours or equipotential lines are closely spaced and roughly parallel land surface. This reflects the depth at which the fractures tend to disappear. The hydrologic cross section shows that fluid movement, both contaminants and ground water, is largely limited to the upper 50 feet of the strata.

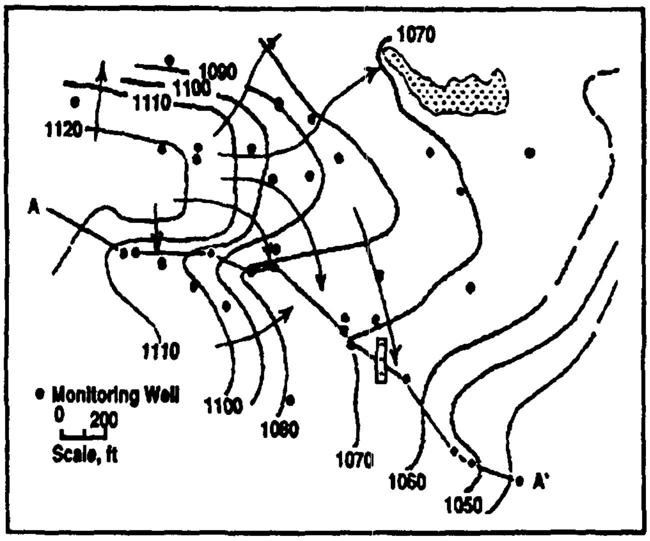

Figure 7-2. Map Showing Configuration of the Water Table and Flow Lines

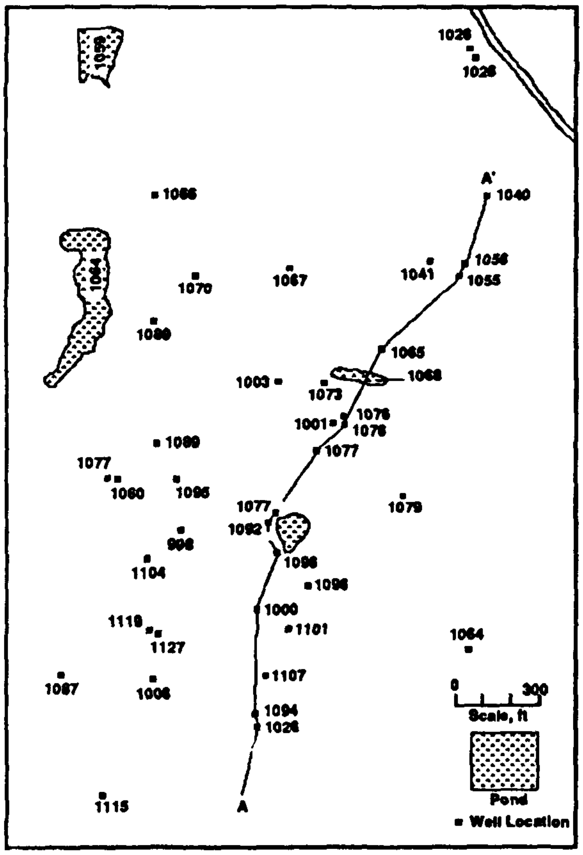

Figure 7-1. Map of a Contaminated Area Showing Location of Monitoring Wells and Elevation of Water Levels

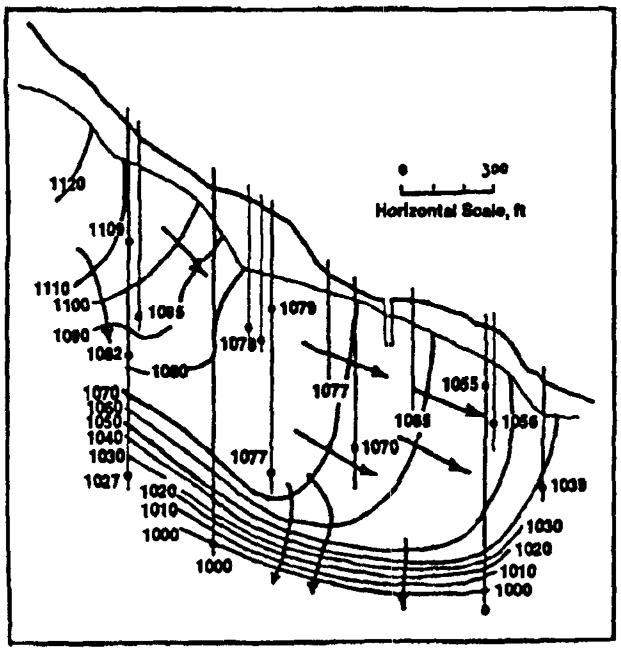

Figure 7-3. Hydrologic Cross Section Showing Equipotential and Flow Lines. Numbers Represent Total Head

Obviously, in either pump-and-treat or in situ restoration systems, or in ground-water monitoring, the location, depth, and length of the screens of monitoring or extraction wells are of paramount importance. If the wells are improperly located, monitoring results would not adequately represent the aquifer being studied, and its restoration would be more costly and less effective than necessary. Therefore, in planning and carrying out ground-water restoration activities, it is essential to dedicate adequate resources to the collection of background information. In designing remediation activities, it is more important to describe the most permeable zones so that it can be determined where the water can go, under a remediation system, rather than its natural state.

Source Control

The objective of source- control strategies is to reduce or eliminate the volume of waste, thereby removing or minimizing ongoing contamination of the ground-water environment. Source-control techniques include removal of the source(s), surface-water controls, ground-water barriers, interceptors, and hydrodynamic controls.

Source Removal

Soil and water at a hazardous waste site may be removed for treatment or relocation to a site that is more acceptable from an engineering or environmental viewpoint. While the removal and treatment or reburial of contaminated materials at a more controlled site may appear to solve a contamination problem, various factors need to be evaluated before excavation commences. These factors include:

(1). Problems associated with the excavation of bulky, partially decomposed or hazardous waste.
(2). Distance to an acceptable treatment/reburial site.
(3). Road conditions between sites.
(4). Accessibility of both sites.
(5). Political, social, and economic factors associated with locating a new site.
(6). Disposition of contaminated ground water.
(7). Control of nuisances and vectors during excavation.
(8). Reclamation of excavated site.
(9). Costs.

These considerations suggest that excavation and relocation may be a viable alternative only where costs are not significant compared to the importance of the resource being protected. In some cases, removal and reburial in an approved facility transfers a problem from one location to another, and possibly creates additional problems.

Surface Runoff Controls

Surface runoff control measures are used to minimize the infiltration and percolation of overland flow or precipitation at a waste site. It is the infiltration of these waters that serve as the moving or driving force that leaches contaminants from the surface or unsaturated zone to the water table. According to an EPA estimate (Schuller and others, 1983), a disposal site consisting of 17 acres with 10 inches per year of infiltration could produce 4.6 million gallons of leachate each year for 50 to 100 years. This estimate, of course, is site-specific. Reduction of infiltration through a contaminated site can be accomplished by contouring the site, providing a cap or barrier to infiltration, and revegetating the site.

Several standard engineering techniques can be used to change the topographic configuration of the land surface in order to control the movement of overland flow. Some of the more common techniques are dikes and berms, ditches, diversion waterways, terraces, benches, chutes, downpipes, levees, sedimentation basins, and surface grading.

A mounded and maintained cover or cap of low permeability material greatly reduces or even prevents water from entering the source, thus reducing leachate generation. Covers also can control vapors or gases produced in a landfill. They may be constructed of native soils, clays, synthetic membranes, soil cement, bituminous concrete, or asphalt, a combination of these materials.

Revegetation can be a cost-effective method of stabilizing the surface of a waste site, especially when preceded by capping and contouring. Vegetation reduces raindrop impact and the velocity of overland flow, and strengthens the soil mass, thereby reducing erosion by wind and water. It also improves the site aesthetically.

Schuller and others (1983) described the effect of regrading, installation of a PVC topseal, and revegetation of a landfill in Windham, Connecticut. As Figures 7-4 and 7-5 illustrate, field data clearly indicate that the cover reduced infiltration and leachate generation, which caused a reduction in the size and concentration of the leachate plume.

Ground-Water Barriers

Subsurface barriers are designed to prevent or control ground-water flow into, through, or from a certain location. Barriers keep fresh ground water from coming into contact with a contaminated aquifer zone or ground

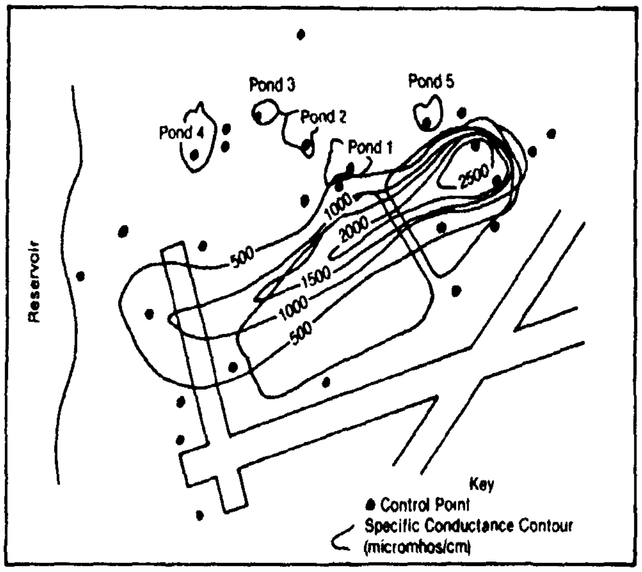

Figure 7-4. Distribution of Specific Conductance, May 19, 1981

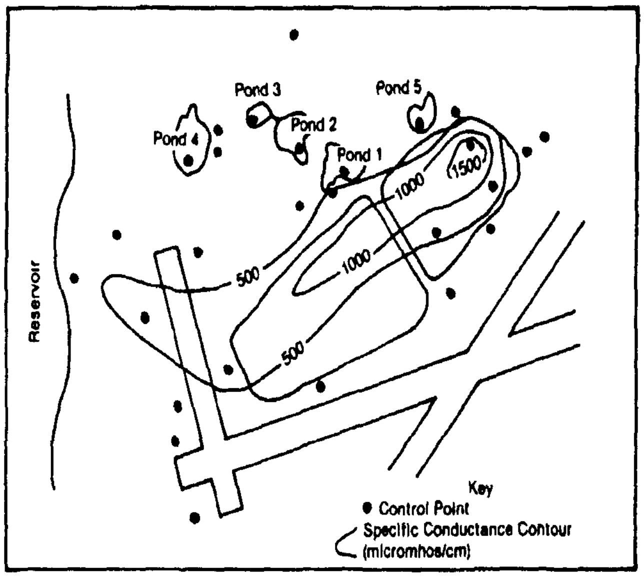

Figure 7-5. Distribution of Specific Conductance, November 12, 1981

water from existing areas of contamination from moving into areas of clean ground water. Usually it is necessary to incorporate other technologies, such as pump-and-treat systems, with ground-water barriers.

The types of barriers commonly used include:

1. Slurry trench walls
2. Grout curtains
3. Vibrating beam walls
4. Bottom sealing
5. Block displacement

Slurry trench walls are placed either upgradient from a waste site to prevent flow of ground water into the site, downgradient to prevent offsite flow of contaminated water, or around a source to contain the contaminated ground water. A slurry wall may extend through the water-bearing zone of concern, or it may extend only several feet below the water table to act as a barrier to floating contaminants. In the former case, the foundation should lie on, or preferably in, an underlying unit of low permeability so that contaminants do not flow under the wall. A slurry wall is constructed by excavating a trench at the proper location and to the desired depth, while keeping the trench filled with a clay slurry composed of a 5 to 7 percent by weight suspension of bentonite in water. The slurry maintains the vertical stability of the trench walls and forms a low permeability filter cake on the walls of the trench. As the slurry trench is excavated, it is simultaneously backfilled with a material that forms the final wall. The three major types of slurry backfill mixtures are soil bentonite, cement bentonite, and concrete. Slurry walls, under proper conditions, can be constructed to depths of 100 feet or so.

Slurry trench walls are reported to have a long service life and short construction time, cause minimal environmental impact during construction, and be a cost-effective method for enclosing large areas under certain conditions (Nielsen, 1983). A concern regarding the use of a slurry wall where contaminated materials are in direct contact with the wall is the long-term integrity of the wall (Wagner and others, 1986). In such cases, the condition of the wall needs to be verified over time by ground-water monitoring.

Two separate slurry walls were constructed along parts of the margin of the Rocky Mountain Arsenal near Denver in order to contain plumes that originate on the plant property (Shukle, 1982, Pendrell and Zeltinger, 1983, and Hager and others, 1983). Along the north boundary, where surficial, unconsolidated sand and gravel occur with a thickness that averages about 30 feet, the slurry wall, about 2 feet thick, is 6,800 feet long. On the upgradient side are a series of 35 12-inch-diameter discharging wells on 200 foot centers that pump contaminated ground water into a treatment facility. After flowing through a carbon filtration system the water is reinjected into 50 6-inch diameter recharge wells on 100 foot centers on the opposite side of the barrier.

Along the northwest boundary of the Arsenal is another bentonite slurry barrier, 1,425 feet long, that extends southwestward from a bedrock high. The wall, excavated into the sand and gravel with the bentonite slurry trench method, is 30 inches wide and extends 3 feet into the underlying bedrock. The barrier contains about 7,000 cubic yards of backfill that were obtained from a borrow pit and blended with the bentonite prior to emplacement. The barrier was constructed where the saturated thickness of the permeable material is less than 10 feet. Paralleling the downgradient side of the barrier is a series of 21 recharge wells, stretching nearly 2,100 feet along the Arsenal boundary. Directly behind (upgradient) the barrier and extending into the thicker part of the surficial aquifer are 15 discharge wells. The contaminated ground water is pumped to a treatment plant and then reinjected into the recharge wells, thus forming a hydraulic barrier. Farther southeast along the boundary is another hydraulic barrier system, about 1,500 feet long, that consists of two parallel rows of discharge wells with 15 wells per row and, downgradient, a row of 14 recharge wells. The contaminated water, originating from a spill, is pumped, treated, and then reinjected. This system and the one along the north boundary was put into operation in late 1981 and the system along the northwest boundary began operation in 1984.

Grouting is the process of pressure-injecting stabilizing materials into the subsurface to fill and, thereby, seal voids, cracks, fissures, or other openings. Grout curtains are underground physical barriers formed by injecting grout through tubes. The amount of grout needed is a function of the available void space, the density of the grout, and the pressures used in setting the grout. Two or more rows of grout are normally required to provide a good seal. The grout used may be either particulate (i.e., Portland cement) or chemical (i.e., sodium silicate) depending on the soil type and the contaminant present. Grouting creates a fairly effective barrier to ground-water movement, although the degree of completeness of the grout curtain is difficult to ascertain (Nielsen, 1983). Incomplete penetration of the grout into the voids of the earth material permits leakage through the curtain.

A variation of the grout curtain is the vibrating beam technique for placing thin (approximately 4 inches) curtains or walls. Although this type of barrier is sometimes called a slurry wall, it is more closely related to a grout curtain since the slurry is injected through a pipe in a manner similar to grouting. A suspended I-beam connected to a vibrating driver-extractor is vibrated through the ground to the desired depth. As the beam is raised at a controlled rate, slurry is injected through a set of nozzles at the base of the beam, filling the void left by the beam's withdrawal. The vibrating beam technique is most efficient in loose, unconsolidated deposits, such as sand and gravel.

Another method that uses grouting is bottom sealing, where grout is injected through drill holes to form a horizontal or curved barrier below the site to prevent downward migration of contaminants.

Block displacement is a relatively new plume management method, in which a slurry is injected so that it forms a subsurface barrier around and below a specific mass or "block" of material. Continued pressure injection of the slurry produces an uplift force on the bottom of the block, resulting in a vertical displacement proportional to the slurry volume pumped. Brunsing and Cleary (1983) described an example of slurry-induced block displacement. Demonstrated in Whitehouse, Florida, a slurry wall was constructed around a small area, 60 feet in diameter, to a depth of 23 feet in unconsolidated material. Injection wells were then used to force a soil bentonite slurry outward along the bottom of the cell. Subsequent test holes indicated that the new floor of the cell contained 5 to 12 inches of slurry.

Sheet pile cutoff walls have been used for many years for excavation bracing and dewatering. Where conditions are favorable, depths of 100 feet or more can be achieved. Sheet piling cutoff walls can be made of wood, reinforced concrete, or steel, with steel being the most effective material for constructing a ground-water barrier. The construction of a sheet pile cutoff wall involves driving interlocking sheet piles down through unconsolidated materials to a unit of low permeability. Individual sheet piles are connected along the edges with various types of interlocking joints. Unfortunately, sheet piling is seldom water-tight and individual plates can move laterally several to several tens of feet while being driven. Acidic or alkaline solutions, as well as some organic compounds, can reduce the expected life of the system.

Membrane and synthetic sheet curtains can be used in applications similar to grout curtains and sheet piling. With this method, the membrane is placed in a trench surrounding or upgradient of the plume, thereby enclosing the contaminated source or diverting ground-water flow around it. Placing a membrane liner in a slurry trench application also has been tried on a limited basis. Attaching the membrane to an underlying confining layer and forming perfect seals between the sheets is difficult but necessary in order for membranes and other synthetic sheet curtains to be effective. Arlotta and others (1983) described a system that consists of a trench lined with 100 mil high density polyethylene and backfilled with sand. It was installed by the slurry trench construction method in New Brunswick, New Jersey, in the fall of 1982.

Hydrodynamic Controls

Hydrodynamic controls are used to isolate a plume of contamination from the normal ground-water flow regime to prevent the plume from moving into a well field, another aquifer, or to surface water. Controlling the movement of ground water by means of recharge and discharge wells has been practiced for several years. The major disadvantages include the commonly long pumping periods, well construction and maintenance costs, and the fact that the subsurface geology dictates system design.

The extent of the cone of depression around a pumping well can be controlled by the discharge rate and thus the cone, which is a change in the hydraulic gradient, can be used to control ground-water flow directions and velocity. Management of the cone or cones permits the operator to capture contaminants, which can then be diverted to a treatment plant. Well placement is particularly important since proper spacing and pumping rates are required to capture the contaminants. Moreover, well placement should be optimized so that as little uncontaminated water as possible is produced in order to reduce treatment costs.

Recharge wells are used to develop a hydraulic barrier (an inverted cone of depression) or pressure ridge. In this way, recharge wells can be used to force the contaminant plume to move in preferred directions, such as toward a drain or discharging well.

The design of well systems is, in large part, based on trial and error methods coupled with experience. Herein also lies one of the more useful exercises of computer simulations, because with this approach one can quickly and easily evaluate different well location and pumping schedules, and estimate costs.

Gradient-control techniques are used at a great number of sites undergoing restoration and nearly always play some role in containment methods, as is the case at the Rocky Mountain Arsenal.

A well point system, which is a common technique used for dewatering at construction sites, consists of several closely spaced shallow wells connected to a main header pipe. The header pipe is connected to a suction lift pump. Well point systems are used only for shallow aquifers and are designed so that the drawdown produced by the system completely intercepts the plume of contamination.

Deep wells are similar to well point systems except they are generally deeper and normally are pumped individually. This system commonly is used in places where the ground-water surface is too deep for the use of a suction lift system.

A thorough knowledge of the hydrogeological conditions of a site is required for the development of a hydrodynamic control system. The effect of the injection wells on the drawdown and the radius of influence of the pumping wells must be analyzed. Of particular importance are the potential well yield or injection rate, and the effect of hydrologic flow boundaries. Monitoring of the system is essential.

Ground-Water Collection and Treatment

The cleanup of a contaminated ground-water site involves the collection and treatment of the contaminated water. Some of the techniques used for source control often are used as part of a ground-water cleanup program, including pumping well systems, interceptor systems, and some of the techniques used for source control. In addition, in situ treatment, enhanced desorption, encapsulation, and biodegradation may be part of a cleanup plan.

Pumping Systems

A ground-water pumping scheme combined with a treatment procedure, also called a pump-and-treat system, is usually designed for a specific ground-water contamination problem. The use of pump-and-treat systems is probably more widespread and successful than all other restoration techniques combined. Large expenditures are made each year to prepare for and operate pump-and-treat remediation of ground-water contamination (Keely, 1989). The hydrogeology of the site, the source of the contaminant, and the characteristics of the contaminant must be understood if an efficient and cost-effective program is to be conducted.

The operation of a well field to remove ground water causes the formation of stagnation zones downgradient from the extraction wells, which must be considered in the system design. For example, if remedial action wells are located within the bounds of a contaminant plume, the portion of the plume lying within the stagnation zones will not be effectively remediated because the contaminants are removed only from the zone of advective ground-water flow. In this case, the only remediation in the stagnation zone will result from the process of chemical diffusion and degradation, which may be very slow. Proper location of wells based on pumping rates and drawdown tends to mitigate this effect.

The tailing effect also can affect the removal and renovation of ground water containing a low solubility contaminant. Tailing is the slow, nearly asymptotic decrease in contaminant concentration in ground water moving through contaminated geologic material. The contaminants migrate into the finer pore structures of the earth materials and are slowly exchanged with the bulk water present in larger pores and this results in "tailing."

Many human-made and natural organic compounds found in ground water tend to adsorb to the organic and mineral components of the aquifer material. When water is removed by pumping, contaminants can remain on the aquifer material, the amount depending on the geologic materials and characteristics of the contaminants. Once sorbed to the geologic material, contaminants may desorb slowly into the ground water, thus requiring extended periods of pumping and treating to attain desired levels of restoration.

The removal of a water-insoluble liquid, such as gasoline, can be difficult since the product may become trapped in the pores of earth materials and is not easily removed by pumping. Pumping ground water to remove the components of a residual phase initially may reduce the concentration, but this reduction may only be the result of dilution or lowering of the water table below the level of contamination. A contaminant will not be removed faster than it is released into the ground water, so if the pumping stops for a period of time, water-soluble residual phase components again will dissolve into the ground water bringing the concentrations back to the previous level.

An innovation in pump-and-treat technology is pulsed pumping. This technique involves alternating the periods of pumping, allowing contaminants time to come to equilibrium with the ground water in each cycle. Equilibrium is achieved by diffusion from stagnant zones or zones of lower permeability, and by partitioning of sorbed contaminants or those associated with residual contaminant phases. Alternating pumping among wells also can establish active flow paths in the stagnant zones.

Another innovation is the use of pump-and-treat systems in conjunction with other remediation technologies. Examples are the use of extraction wells with barrier walls to limit plume expansion while reducing the amount of clean water pumped, and the use of surface ponds or flooding to flush contaminants from the unsaturated zone prior to collection by a pumping system.

Interceptor Systems

Interceptor systems may be an alternate to pumping systems. The subsurface drains used in interceptor systems essentially function as an infinite line of extraction wells, and can perform many of the same functions. Subsurface drains create a continuous zone of influence in which ground water flows towards the drain. Subsurface drains are installed perpendicular to the direction of ground-water flow and collect ground water from an upgradient source for treatment. Interceptor systems prevent leachate or contaminated ground water from moving downgradient toward wells or surface water.

Two types of interceptor systems used for source control are the passive system, which relies on gravity flow, and the active system, which uses pumps. An interceptor system consists of a trench excavated to a specified depth below the water table in which a perforated collection pipe is installed in the bottom. Active interceptor systems have vertical removal wells spaced along the interceptor trench or a horizontal removal pipe in the bottom of the trench. Active systems are usually backfilled with a coarse sand or gravel to maintain the stability of the wall. These interceptor systems can be used as preventive measures, such as leachate collection systems, as abatement measures, such as interceptor drains, or in product recovery from ground water, such as the removal of gasoline or oil. Interceptor drains generally are used to either lower the water table beneath a contamination source or to collect contaminated ground water from an upgradient source. Interceptor systems are relatively inexpensive to install and operate, but they are not well suited for soils with a low permeability.

In stratified soils with variable hydraulic conductivities, the drain is normally installed on a layer with a low hydraulic conductivity to minimize leachate leakage under the drain. An impermeable liner placed in the bottom of a trench also can be used to control underflow. The design, spacing, and location of drains for various soil and ground water conditions are described further in Wagner and others (1986).

A combined interceptor and ground-water dam installation was described by Giddings (1982). In this case, a landfill that began as a burning dump, was found to be discharging leachate both to the surface and to the ground water, much of which eventually flowed into an adjacent river. A leachate interceptor trench was constructed on the downgradient side of the disposal area, as shown in Figure 7-6. In the trench on the upgradient side was placed a perforated pipe in a gravel envelope that was covered with permeable material. The remainder of the trench on the downgradient side was then backfilled with fine-grained materials as shown in Figure 7-7. Leachate from the landfill flows into the filled trench, seeps into the perforated pipe, and then is collected for treatment. In this case, the main

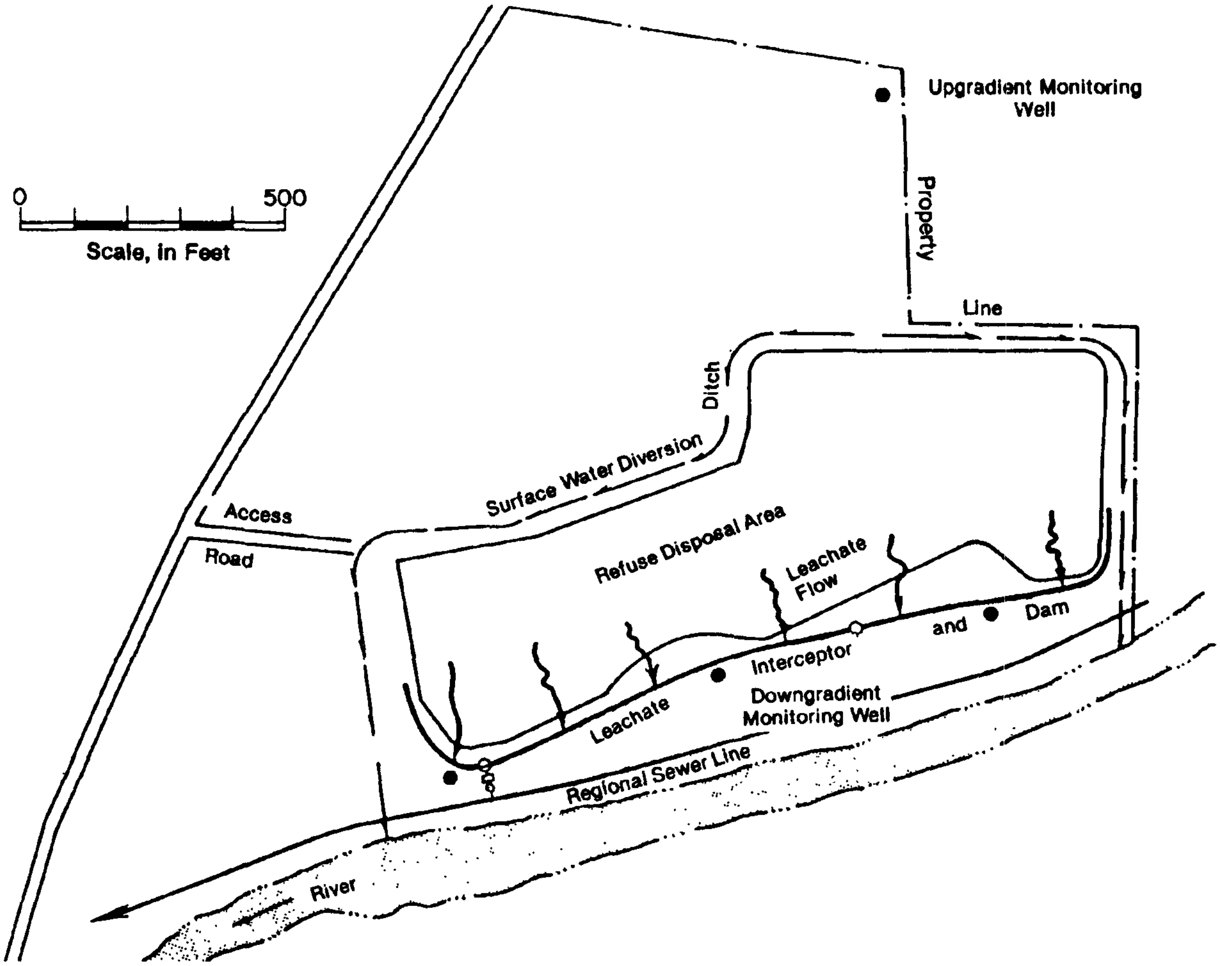

Figure 7-6. Site Layout

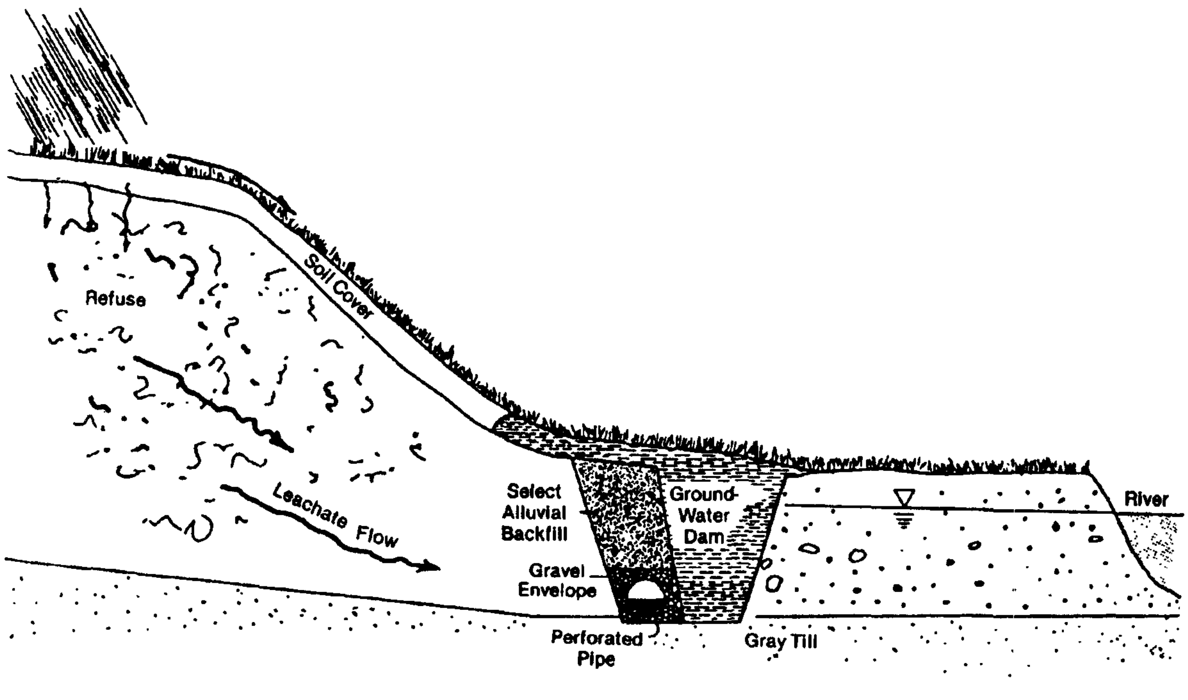

Figure 7-7. Site Cross Section

purpose of the ground-water dam was to prohibit water originating in the adjacent river from flowing into the trench, which would have substantially increased the volume of wastewater.

Ground-Water Treatment after Removal

Of course the technology of pumping and treating of ground water implies that a cadre of engineering processes are available for treating the extracted water at the surface. A detailed discussion of these is beyond the scope of this document. They will only be mentioned to give the reader a familiarity with the processes so that detailed searches can be made elsewhere.

Treatment technologies for pumped or intercepted ground water can be grouped into three broad areas: physical, chemical, and biological. Physical treatment methods include adsorption, density separation, filtration, reverse osmosis, air and steam stripping, and incineration. Precipitation, oxidation/reduction, ion exchange, and neutralization are commonly used chemical treatment methods. Biological treatment methods include activated sludge, aerated surface impoundments, anaerobic digestion, trickling filters, and rotating biological discs.

In Situ Treatment

In situ treatment is an alternative to the removal and subsequent treatment of contaminated ground water. This method requires minimal surface facilities and reduces exposure to the contaminant. The success of various treatment methods is highly dependent on physical factors including aquifer permeability, the characteristics of the contaminants involved, and the geochemistry of the aquifer material.

In situ treatment technology has not yet been developed to the extent of other currently available technologies for restoring contaminated aquifers. However, some in situ treatment technologies have demonstrated success in actual site remediations (Wagner and others, 1986). Laboratory and pilot-scale testing generally must be performed to evaluate the applicability of a particular technology to a specific site.

In situ treatment may be grouped into two broad categories: physical/chemical and biological. Brief descriptions follow of the available technologies that have potential for success at hazardous waste sites.

In Situ Physical/Chemical Treatment

Organic and inorganic contaminants may be treated chemically to cause immobilization, mobilization for extraction, or detoxification. The application of oxidation and reduction reactions to in situ treatment is largely conceptual, but potentially may be used to accomplish immobilization by precipitation, mobilization by solubilizing metals or organics, or detoxification of metals and organics (Wagner and others, 1986). The chemicals used in these processes, however, have the potential to degrade compounds other than those targeted and to form degradation products that may be more toxic than the original ones.

Precipitation, chelation, and polymerization are three methods used to immobilize a contaminant. Precipitation using caustic solutions is effective in immobilizing dissolved metals in ground water. Chelation also may be effective in immobilizing metals, although considerable research is needed (Wagner and others, 1986). Polymerization is effective in immobilizing organic monomers. However, the chemicals added to the contaminants in the ground water may react to form toxic by-products. Solidification methods used for treatment of soils also can immobilize contaminants. Mobilization of contaminants is accomplished by soil flushing or vacuum extraction. Neutralization, hydrolysis, and permeable treatment bed technologies may be used for detoxification. Precipitation and polymerization will lower the hydraulic conductivities near the injection wells making closely spaced wells necessary for effective treatment.

One interesting example of polymerization, reported by Williams (1982), involved a 4,200 gallon leak of acrylate monomer from a corroded pipeline at a small plant in Ohio. The contaminant migrated through a layer of fill, consisting largely of cinders, and then downward through a storm sewer trench into a thin sand and gravel aquifer. A test boring and soil sampling program delineated the plume and indicated that the contaminant was slowly beginning to undergo polymerization and, therefore, immobilization. To increase the rate of reaction, 2-inch-diameter perforated PVC pipe was buried, about 2 feet below land surface, in four narrow trenches that trended across the plume. A riser and manifold header connected each pipe to solution tanks containing a catalyst in one and an activator in the other. Both solutions contained a wetting agent. A total of 8,000 gallons of solution were injected during the two treatment operations and 1,000 gallons had been injected previously during the investigative phase. On the basis of pre- and post-treatment soil borings, it was estimated that 85 to 90 percent of the liquid monomer contaminant was solidified, and in some places it exceeded 99 percent polymerization. It was assumed that the remaining material would polymerize naturally.

In situ physical/chemical treatment processes generally entail the installation of a series of injection wells at the head of or within the plume of contaminated ground water. An alternative technique that has been used in shallow aquifers, is the installation of in situ permeable treatment beds. Trenches are filled with a reactive permeable medium and contaminated ground water entering the trench reacts with the medium to produce a nonhazardous soluble product or a solid precipitate. Among the materials commonly used in permeable bed trenches are limestone to neutralize acidic ground water and remove heavy metals, activated carbon to remove nonpolar contaminants, such as carbon tetrachloride, polychlorinated biphenyls, and benzene, and zeolites and other ion exchange resins for removing solubilized heavy metals.

Permeable treatment beds are applicable only in relatively shallow aquifers because the trench must be constructed down to a layer of low permeability. They also are often effective for only a short time because they lose their reactive capacity or become plugged with solids. An over design of the system or replacement of the reactive medium can lengthen the time during which permeable treatment is effective.

Mobilization for Extraction

Pump-and-treat remediation techniques often are inefficient when a preponderance of the contaminants are sorbed to the solid phase of the aquifer. The same can be said for in situ treatment if the reactive chemicals are unable to come into contact with the contaminants. In these cases, the enhanced desorption or mobilization of contaminants would be of considerable interest in aquifer restoration activities.

Soil flushing is the process of flooding a contaminated area with water or a solvent to mobilize the contaminant, followed by the collection of the elutriate. The process is based on the solvent solubilizing or chemically reacting with the contaminants and mobilizing them into the solvent phase. Water is used if the contaminant is readily soluble. Acid solutions tend to flush metals and basic organics.

The mobilization of contaminants by injecting surfactants into the aquifer matrix is possible. Techniques used for the secondary recovery of oil are being used experimentally, with moderate success. Both surfactant and alkaline floods have been attempted. Most oil-field surfactants are expensive, while alkaline floods produce lye; therefore, this approach promises little benefit to aquifer restoration.

In the recovery of hydrocarbons, there are three possible physical-chemical methods. At shallow depths, thermal or steam flooding may be helpful while on a larger scale, alcohol flooding may at some future date prove to be helpful. Alcohol is easily produced and dissolves the hydrocarbon, but tentative research results indicate that the required alcohol-water ratio must be so high as to make the technique questionable.

Another emerging technology, which is increasingly being used, is alternately called in situ vacuum extraction or in situ volatilization. It is used to extract volatile organic contaminants from the unsaturated zone where contaminants exist as a result of underlying contaminated ground water, or free product riding on top of the ground water, or from leaks or spills. The technology has enjoyed considerable success in this and other industrialized countries.

The plumbing associated with this type of remediation is obviously dictated by site conditions, including the thickness of the unsaturated zone, the volatility of the contaminants involved as well as their source and extent, and the porosity and permeability of the unsaturated zone (Pacific Environmental Services, 1989).

Generally these vapor extraction projects consists of a series of slotted PVC wells configured to span the area of contamination. Air inlet wells located both inside and outside of the plume increase the introduction of air from the atmosphere (fig. 7-8).

Like pump-and-treat remediation techniques, vacuum extraction projects usually require some type of surface treatment facility to deal with the collected vapors. When surface treatment is required, activated carbon columns are widely in operation, however the use of biologically active columns is being studied, which will allow the introduction of oxygen or other gases needed for biodegradation.

Vacuum extraction is best suited for areas of high, relatively homogeneous, permeability. There should be no underground structures, and great care must be given to the explosive nature of the extracted vapors. The unit cost, which appears to be very promising, varies widely according to the size of the area under remediation and the specific site characteristics.

Radio frequency heating has been under development since the mid-1970s and the concept is being applied to in situ decontamination of uncontrolled hazardous waste landfills and sites (Rich and Cherry, 1987). In this process, the ground is heated with radio frequency waves that vaporize the hazardous contaminants. The vapors emanating from the soil are then treated.

Detoxification

Neutralization of ground water may be accomplished by injecting dilute acids or bases into the aquifer through

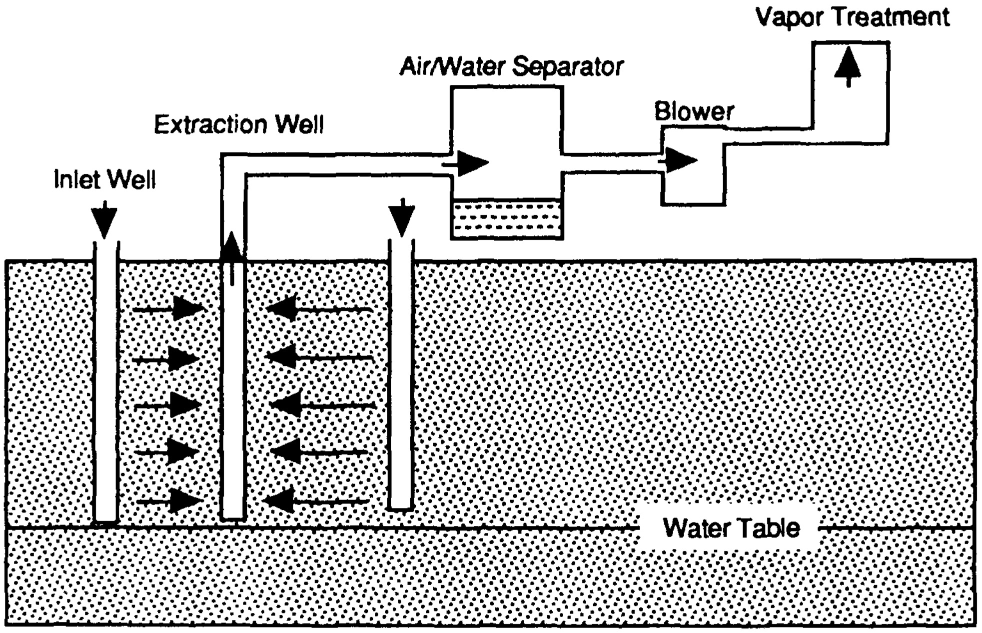

Figure 7-8. Schematic of a Vaccum Extraction System

injection wells to adjust the pH to the desired level. Tolman and others (1978) recommended that neutralization only be applied to ground water at industrial waste disposal sites since municipal landfills, which constantly generate anaerobic decomposition products, would require neutralization over a long period of time.

Hydrolysis may be used for detoxification, however, the intermediate products formed during hydrolysis of a particular compound must be known since they may be more toxic than the targeted compound. Esters, amides, carbamates, phosphoric and phosphonic acid esters, and pesticides are potentially degradable by hydrolysis (Wagner and others, 1986).

Biodegradation

There are two basic approaches to in situ biodegradation. The first relies on the natural biological activity in the subsurface. The second approach, called enhanced biorestoration, involves the stimulation of the existing microorganisms by adding nutrients.

Natural Subsurface Biological Activity

Biological treatment in the subsurface involves the use of microorganisms to break down hazardous organic compounds into nonhazardous materials. The site hydrology, environmental conditions, and the biodegradability of the contaminants are factors that determine the potential effectiveness of in situ biological treatment. Most compounds are more rapidly degraded aerobically, however some compounds will only degrade under anaerobic conditions. Biodegradation in ground water and solids can be a slow process and may take several years for completion depending on the compounds present. In situ biodegradation, however, is a desirable method of treatment because the contaminants are destroyed, thus, removal of ground water for external treatment and residual handling possibly can be avoided.

In situ biorestoration of the subsurface is a relatively new technology that has recently gained considerable attention. Scarcely more than a decade ago, conventional wisdom assumed that the subsurface below the root zone of plants was, for all practical purposes, sterile. Research during the last decade has indicated that the deeper subsurface is not sterile, but in fact, harbors significant populations of microorganisms. Bacterial densities of around a million organisms per gram of dry soil have been found in several uncontaminated aquifers. Water-table aquifers examined so far exhibit considerable variation in the rate of biodegradation of specific contaminants and rates can vary two or three orders of magnitude from one aquifer to another or over a vertical separation of only a few feet in the same aquifer. Although extremely variable, the rates of biodegradation are fast enough to protect ground-water quality in many aquifers.

Although not clearly defined, several environmental factors are known to influence the capacity of indigenous microbial populations to degrade contaminants. These factors include dissolved oxygen, pH, temperature, oxidation-reduction potential, availability of mineral nutrients, salinity, soil moisture, the concentration of specific contaminants, and the nutritional quality of dissolved organic carbon in ground water.

Natural biorestoration does occur in the subsurface environment. Contaminants in solution in ground water, as well as vapors in the unsaturated zone, can be completely degraded or transformed to new compounds. Undoubtedly, thousands of contamination events are remediated naturally before the contamination reaches a point of detection. On the other hand, methods are needed to determine when natural biorestoration is occurring, the stage the restoration is in, whether enhancement of the process is possible or desirable, and what will happen if natural processes are allowed to run their course.

For information on in situ biorestoration of specific compounds and conditions see Bower and McCarty (1983), Jhaveri and Mazzacca (1983), Lee and Ward (1984), Parsons and others (1985), Parsons and others (1984), Sulflita and Gibson (1985), Sulflita and Miller (1985), Wilson (1985), Wilson and Rees (1985), Wood and others (1985), and Young (1984).

Enhanced Biorestoration

In the subsurface environment, populations of organisms capable of degrading contaminants increase until limited by metabolic requirements, such as mineral nutrients or oxygen. Once this point is reached, the rate of biodegradation or transformation of organic compounds is controlled by the transport mechanisms that supply the limiting nutrients.

The majority of microbes in the subsurface are firmly attached to soil particles. As a result, nutrients must be brought to the active sites by advection and diffusion of water in the saturated zone, or by soil gas, in the unsaturated zone. In the simplest and perhaps most common case, the compounds to be degraded for microbial energy and cell synthesis are transported in the aqueous phase by infiltrating water or by advective flow through the ground water. In the unsaturated zone, volatile organic compounds can move readily as vapors in the soil gas where oxygen is present. Below the water table, aerobic metabolism is limited by the low solubility of oxygen in water. Factors that control the rate of biological activity are the stoichiometry of the metabolic process, the concentration of the required nutrients in the mobile phases, the flow of the mobile phases, the opportunity for colonization in the subsurface by metabolically capable organisms, and the toxicity of the waste.

Much of the development work in the area of ground-water and soil remediation by biodegradation has been performed using petroleum products. The number of gasoline stations, underground tanks, and gasoline pipelines throughout the country and the potential for ground-water contamination have prompted considerable laboratory and field studies on in situ biodegradation of hydrocarbons.

Many of the enhanced biorestoration techniques now in use are variations on those developed by Raymond and his coworkers (Raymond, 1974; Raymond and others, 1986). This process reduces hydrocarbon contaminants in aquifers by enhancing the indigenous hydrocarbon-utilizing microflora. Nutrients and oxygen are introduced through injection wells and circulated through the contaminated zone by pumping one or more producing wells. The increased supply of nutrients and oxygen stimulates biodegradation of the hydrocarbons.

Raymond's process has been used with reasonable success to restore aquifers contaminated with gasoline. The overall removal of total hydrocarbons using this technology usually ranges from 70 to 80 percent. Some of the sites treated by this technique have been restored to the point where no dissolved gasoline was present in the ground water, and state regulatory standards were satisfied. State agencies charged with restoring other sites, however, have required that the operation continue until no trace of liquid gasoline could be detected. Most of the sites restored in this manner have had appropriate monitoring programs installed following remediation.

Usually the first step in the process is to use physical methods to recover as much of the gasoline as possible and then a detailed investigation of the hydrogeology is undertaken to determine the extent of the contamination. Laboratory studies are conducted to determine if the native microbes can degrade the contaminants and to determine the combination of minerals required to promote maximum cell growth at the ambient ground-water temperature and under aerobic conditions.

Considerable variations in nutrient requirements among aquifers have been noted. One aquifer required only the addition of nitrogen and phosphorus, while another was best stimulated by the addition of ammonium sulfate, mono- and disodium phosphate, magnesium sulfate, sodium carbonate, calcium chloride, and manganese and ferrous sulfate. It was found that a chemical analysis of the ground water was not helpful in estimating the nutrient requirements of the system.

Field investigations and laboratory studies guide the design and installation of a system of wells for injecting the nutrients and oxygen, and for the control of ground-water flow. Controlling the ground-water flow is critical to moving oxygen and nutrients to the contaminated zone and optimizing the degradation process.

The technique developed by Raymond does not provide for treatment above the water table. Soils contaminated by leaking underground storage tanks may be physically removed during the process of removing the tank, however, this may not be practical with deep water tables or large areas of contamination. An alternative to soil removal is the construction of one or more infiltration galleries, which are used to recirculate the treated water back through the contaminated unsaturated zone. Oxygen may be added to the infiltrated water during an in-line stripping process for volatile organic contaminants or through aeration devices placed in the infiltration galleries.

The rate of biorestoration of hydrocarbons, either above or below the water table, is effectively the rate of supply of oxygen. Table 7-1 compares the number of times the water in the aquifer, or the air above it, must be replaced to restore subsurface materials of various textures. The calculations assume typical values for the volume occupied by air, water and hydrocarbons (De Pastrovich and others, 1979, Clapp and Horberger, 1978). The calculations further assume that the oxygen content of the water is 10 mg/L, that of the air is 200 mg/L and that the hydrocarbons are completely metabolized to carbon dioxide. These values are provided only to exemplify the processes involved and would differ at an actual site. The oxygen concentration in the water can be increased by using oxygen rather than air, which also would reduce the volumes of recirculated water required.

Hydrogen peroxide is an alternative source of oxygen in biorestoration and Raymond and others (1986) have patented a process of treatment with hydrogen peroxide. Iron or an organic catalyst may be used to decompose the hydrogen peroxide to oxygen. The rate at which hydrogen peroxide decomposes to oxygen must be controlled to limit the formation of bubbles that could lead to gas blockage and the loss of permeability. Hydrogen peroxide may mobilize metals, such as lead and antimony, and, if the water is hard, magnesium and calcium phosphates can precipitate and plug the injection well or infiltration gallery. To determine the microorganism's hydrogen peroxide tolerance level laboratory studies are performed.

Treatment Trains

In most contaminated hydrogeologic systems, the remediation process may be so complex, in terms of contaminant behavior and site characteristics, that no single system or unit is capable of meeting all requirements. Consequently, several unit operations may be combined in series or in parallel to effectively restore ground-water quality to the required level. Barriers and hydrodynamic controls may serve as temporary plume control measures, however, hydrodynamic processes are integral parts of any withdrawal and treatment or in situ treatment process.

Most remediation projects typically are started by removing the source. The next step may be the installation of pumping systems to remove free product floating on the water surface or the removal of soluble contaminants for treatment at the surface. Barriers also might be constructed to slow an advancing plume or to reduce the amount of water requiring treatment.

	Proportion of Total Subsurface Volume Occupied by:			Volumes Required to meet Hydrocarbons Oxygen Demand	
Texture	Hydrocarbons (when drained)	Air (when drained)	Water (when flooded)	Air	Water
Stone to Coarse Gravel	0.005	0.4	0.4	250	5,000
Gravel to Coarse Sand	0.008	0.3	0.4	530	8,000
Coarse to Medium Sand	0.015	0.2	0.4	1,500	15,000
Medium to Fine Sand	0.025	0.2	0.4	2,500	25,000
Fine Sand to Silt	0.040	0.2	0.5	4,000	32,000

Table 7-1. Estimated Volumes of Water or Air Required to Completely Renovate Subsurface Material that Contained Hydrocarbons at Residual Saturation

Enhanced biorestoration techniques may be feasible in some of the more diluted areas of the plume. In some circumstances, a site may reach final restoration goals using natural chemical and biological processes. An adequate monitoring program would be required to establish data on the progress of the restoration program.

Steps in treatment of contaminated ground water include the removal, collection, and delivery of the contaminated water to the treatment units, and in the case of in situ processes, delivery of the treatment materials to the contaminated areas in the aquifer. A thorough knowledge and understanding of the hydrogeologic and geochemical characteristics of the site are required to design a system that will optimize the remediation techniques selected, maximize the predictability of restoration effectiveness, and allow for the development of a cost-effective and lasting remediation program.

Institutional Limitations on Controling Ground-Water Contamination

The principal criteria for selecting remediation procedures are the water-quality level to which to restore an aquifer, and the most economical technology available to reach that level. Institutional limitations, however, sometimes override these criteria in determining if, when, and how remediation will be selected and carried out.

Response to a ground-water contamination problem is likely to require compliance with several local, state, and federal pollution control laws and regulations. If the response involves handling hazardous wastes, discharging substances into the air or surface waters, or injecting wastes underground, federal and state pollution control laws will apply. These laws do not exempt the activities of federal, state, or local officials or other parties attempting to remediate contamination problems. They apply to both generators and responding parties, and it is not unusual for these pollution control laws to conflict. A hazardous waste remediation project must meet RCRA permit requirements governing the transport and disposal of hazardous wastes, which can influence the selection of the remediation plan and the scheduling of cleanup activities.

In situ remediation procedures may be subject to permitting or other requirements under federal or state underground injection control programs. Withdrawal and treatment approaches may be subject to regulation under federal or state air pollution control programs or to pretreatment requirements if contaminated ground water is to be discharged to a surface water or to a municipal wastewater treatment system. A remediation plan involving pumping from an aquifer may be subject to state ground-water regulations on well construction and well spacing, and may need to consider various competing legal rights to extract ground water.

Other factors influencing selection and design of a ground-water remediation program include the availability of alternative sources of water supply, political and judicial constraints, and the availability of funds. Where alternate water supplies are plentiful and economical, there may not be a demand for total remediation; adequate remediation to protect human health and the environment may be sufficient. In the final analysis, responsible agencies can pursue remediation measures to the extent that resources are made available.

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