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Service

Principles of Ground Water for Resource Management Systems

Field Level Training Manual

USDA
SCS

PRINCIPLES OF GROUND WATER
for
RESOURCE MANAGEMENT SYSTEMS

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FIELD LEVEL TRAINING MANUAL

Primary Manuscript

prepared by

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Prologue

So there he is again. This is the third time this month that someone had called the Soil Conservation Service field office and asked the district conservationist, Mike Kenton, to come out and take a look down a water well on the west side of Jefferson City. This time it's from the same area as the other two calls, Kuma Estates, just south of the Kuma View Golf Course, right off the I-75 and Norris Road interchange. This time it's the same kind of complaint too, something about a strange taste and smell to someone's well water. On the way over, Kenton had hoped that there would be a simple answer to the problem, but he had his doubts. On the other two occasions about all that he could do was ask the health department to come out and sample the water. Somehow he had a feeling that the situation would be like the previous two and that he wouldn't be of much help. After all he's a soil conservationist, not a chemist or a ground water expert.

As he drives past the golf course he notices that there seem to be many people out playing today. Kenton enjoys a round of golf now and again, when he's got the time, but can't understand why anyone would want to be playing on such a sweltering June day. He wonders why it always seems to be even hotter after a few good soaking thunderstorms.

When he arrives at the address, he finds that this time the situation is worse than he had expected. It seems that the owners of the property, the Johnson family, have noticed a strange taste and smell to their well water, just after the last few rainfalls. Today it's a bit more serious than a bad taste or smell and it's clear that Mr. and Mrs. Johnson are pretty upset. This morning their 10-year-old son, Daniel, complained of stomach cramps, nausea and dizziness, which seemed to have come about just after he had taken a long drink from the garden hose. He had just finished sweeping the driveway of the gravel and debris washed in by yesterday's heavy rains. Luckily the boy seemed to be OK now and was in the house resting. However, Kenton has the feeling that the situation is far from over.

This time Kenton is not the only one who got called. Also present is a woman from the county health department, the assistant city manager and a reporter from the Jefferson City Gazette. The situation is tense and the 90 degree heat is not helping. While Mr. Johnson is undoing the cap to the well located in the side yard, Mrs. Johnson is nervously talking about the episode and the reporter seems to be writing down everything she's saying. She keeps mentioning something about the county incinerator and landfill, north of town along the west side of the river, and how "that's where the bad water is coming from" and that the facility should be closed down. The assistant city manager tries to calm Mrs. Johnson down and promises her that the city landfill is safe because ground water from a well out at that site is sampled and tested every 4 months.

As Kenton stands there and listens, he wonders to himself if what Mrs. Johnson says about the landfill could be true. How could it be? How could it be when the landfill is so far away? And besides, no one living near the landfill is having this problem, so how could it be coming from there? Why isn't the strange smell and taste in the water all the time? Could it be coming from the family's septic tank? It could be any number of things. Kenton looks along the edge of the yard and notices a nice crop of raspberries growing along a drainage ditch. He wonders if maybe the boy just had a few too many of those. Nothing adds up to a stomachache like a 10-year-old and a bunch of unripe berries.

Kenton walks over to the spigot along the edge of the house where the woman from the health department is in the process of filling up a sample bottle with the water. He watches as she fumbles with the loose valve and tries to steady the water flow so it doesn't keep gushing over the top of the bottle. Kenton wants to ask the woman if maybe it wouldn't be better to take a sample directly from the well, since it's open; but it looks like a question that may only irritate her at this moment, so he doesn't ask. Her feet and the cuffs of her slacks are soaked now and she looks pretty frustrated, so he leans over to help her. Finally, they manage to fill the bottle up and she looks for the cap to it. She can't seem to find the one she took off of it so she looks through the bottom of a fancy looking box next to her. She finds another one, wipes it off and seals up the bottle. Kenton has the feeling that she is new to this job. He soon finds out that he's right when she introduces herself as Carin Stevens, and tells him how hectic a week it's been because she just started and two other full-time people have been sick with the flu. Kenton asks her if she knows anything about the analyses done on the well water from this area earlier in the month. She tells him that it will most likely be a couple more weeks before they get the results because they had to send the samples away to be analyzed. She then walks over to her station wagon, places the bottle and box on the hood in the sun and walks back over to the well.

Kenton reaches down to the spigot and fills the palm of his hand with water. He then puts his palm to his mouth and takes a little taste. Sure does have a different taste, almost oily. The smell is something he can't describe. It irritates his nose a bit, almost like ammonia but not quite. For some reason the combination of the smell and taste makes him think of heavy machinery. Perhaps a hint of diesel fuel, maybe trucks or trains. He recalls hearing about some sort of fuel spill in the train yard about 6 months ago, but that was supposedly taken care of by some engineers from the South-Central Railroad, and anyway, that was supposed to be only a few gallons. Funny though, this is the same sort of taste and smell the water had on the two previous calls he had gotten on this side of town earlier this month, only stronger this time. Could it be from one of the nearby farms? Old Roger McCready's big feedlot operation is just a mile or so to the south. There aren't any streams connecting that area with this one though. The district office helped McCready design the drainage for that operation only a couple of years ago and it was a good job. Besides, that area is down the valley from here. How could the water flow uphill? Doesn't the ground water follow the the surface drainage routes? What about pesticide and herbicide use on the surrounding farmlands? How about the chemicals they use on the golf course? The questions kept running through his mind.

Back at the well, the reporter from the Jefferson City Gazette, Skyler Reed, is now throwing around names of local industries and activities, asking if they could be the source of this contamination. No one is saying much. The reporter fishes for a reaction by mentioning several of the bigger companies like Petefish Brothers Incorporated, located near the fairgrounds, and a well known manufacturer of welding equipment and battery chargers; Erinakis Scrap Lead Inc., southwest of the city, a company that recycles lead from batteries; the Shoop Grain and Agri-Center, a regional grain elevator and farm service across the river, out east of the Jefferson City Community Park; and T. Mack Aero-Plastics, makers of special plastics for use in the military and aerospace industry, located in the new industrial park just west of Interstate 75. Some of those same names have come to Kenton's mind, too. He knows that they all deal with materials that if improperly handled or disposed of could cause contamination. There are, however, dozens of other smaller chemical, tool and die, and commercial industries in Jefferson City that could also be sources. At any rate, Kenton knows that before they can find the source, they must first figure out what's in the water.

Holding back any comments, Kenton moves up to take his turn looking down the well. One well looks just like another to him. (There's really no reason why they shouldn't.) There is, however, a strange odor coming from the open well. The reporter asks him what the smell is and where it's coming from. Kenton points down the well and tells the reporter it's coming from there! Visibly frustrated and not amused, the Gazette reporter asks Kenton exactly who he thinks is contaminating the water. Now, Kenton knows that he himself is not an expert on wells or geology, but he probably knows more about such things than anyone else present today. At the moment though, he is a bit baffled. He just doesn't feel he has the background to safely venture a guess as to the source of the problem, at least not one he cares to read about in the afternoon paper!

Most of his expertise involves the upper few feet of soil. Folks around here look to Kenton for his expertise in dealing with agricultural, drainage, erosion and septic problems; that's part of his everyday routine. But this time the problem is coming from deep in the ground. In just a few moments someone is going to ask Kenton what can be done about the problem and he may have to scratch his head with everyone else. Regardless of what is said or done at that moment, it's evident that he hasn't seen the last of this kind of problem and that many more questions are going to be coming through the district office. He may need some help in figuring out the right answers. If he only had a better understanding of ground water. Maybe then he could answer some of the questions, for himself and everyone else involved.

*   *   *   *   *   *

I. Introduction

Purpose

Ground water accounts for 97 percent of all the available fresh water found in the United States. More than half of the general population and almost 95 percent of the rural population relies on ground water as a source of drinking water. Along with the widespread use of ground water there has come a myriad of problems associated with its misuse.

With the increase in ground water contamination, hazardous spills, and water shortages, there is a need for trained professionals to be able to understand the basic concepts of ground water so that the right questions can be asked and the best answers given. SCS field office personnel often find themselves in the position of being called first to deal with ground water questions. In many areas they are the closest thing to a geologist or hydrogeologist there is. The purpose of this course is to extend their knowledge to include the basic principles of ground water. Having a better understanding of these concepts and their applications will help develop the necessary skills to answer ground water questions.

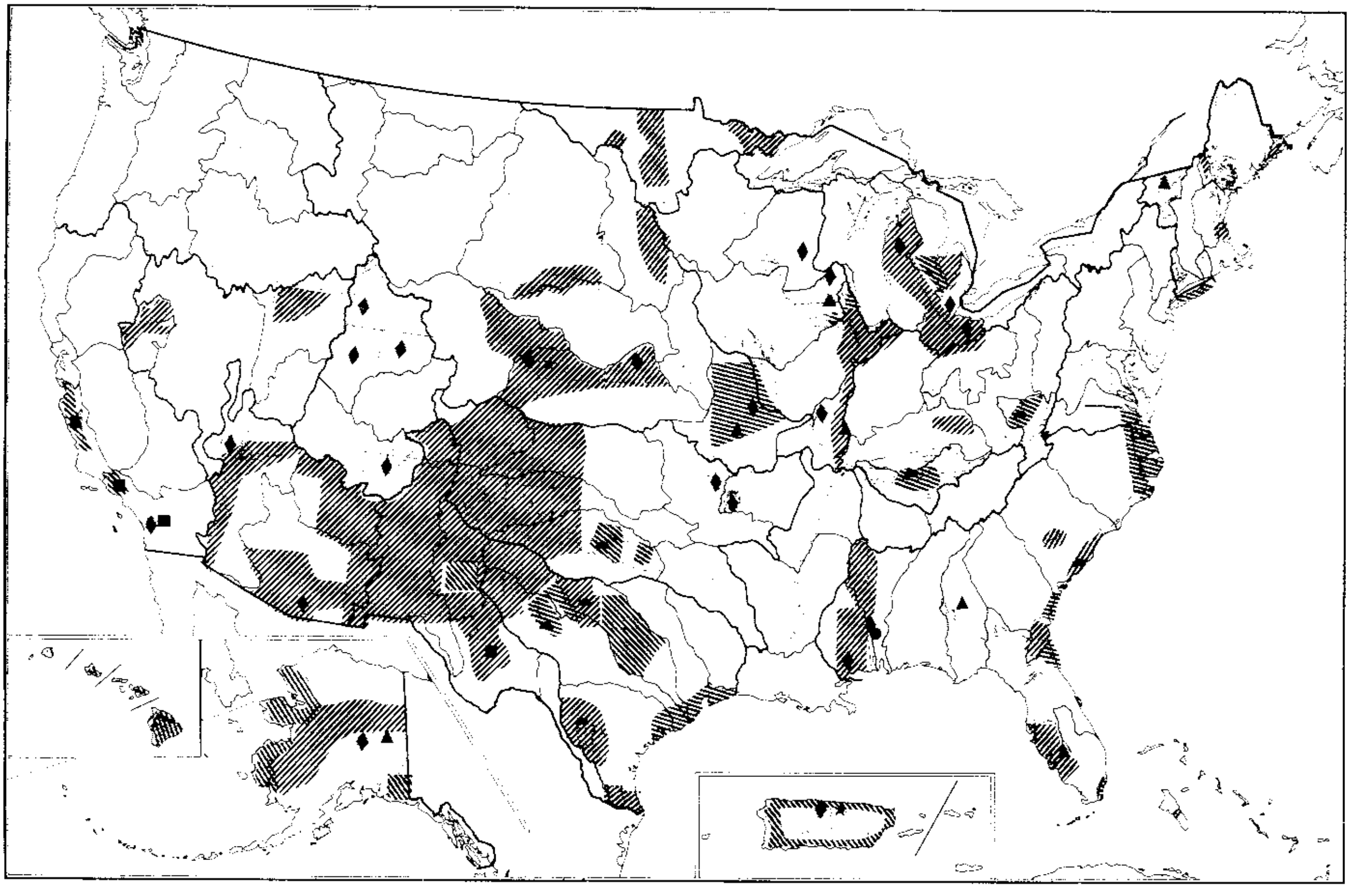
Growing Concern Over Ground Water Resources

In the past, water was not something most of us had to worry about. Always taken for granted, it was simply there when we needed it, cool, clear and clean, a never ending supply. Not many people gave much thought to the possibility of their supply running out or even where it came from. To many people, ground water has always been an accessible and seemingly infinite resource. Ground water use has increased dramatically in recent years due to several advantages it has over surface water. It offers the characteristics of being low in turbidity and contaminants and generally needs relatively little filtration or treatment. In addition, its low temperature is of value in industrial cooling processes and heat exchangers. Because of its widespread distribution, it is generally accessible which results in lower development costs. No surface impoundments or dams are needed to capture it. Its development, when managed properly, can have a minimum impact on the land surface. All in all, ground water is a clean, cool, widespread, accessible, and economical alternative to surface water.

Unfortunately ground water also has the disadvantage of being a hidden resource and one which is often misunderstood. Unlike a lake or a river, ground water is out of sight and subsequently little can be directly perceived about its quality or quantity. In past decades, and at the present, a lack of awareness, respect and foresight has lead to widespread misuse of ground water. Contamination directly from the improper disposal of all forms of waste, application of agricultural chemicals and indirect contamination from polluted surface waters are just a few of the major factors that have lead to the degradation of an alarming portion of the nation's ground water reserves. The map in figure 1-1 shows the distribution of polluted ground water supplies in the United States in 1978. A map like this, made today, would show a large increase in the documented contamination areas because we have increased our efforts to identify and remedy these problems. In some areas, overdraft or "mining" of the ground water has led to depleted quantities, resulting in long term water shortages. Figure 1-2 shows the distribution of areas where ground water resource quantity depletion is of major concern in the U.S. With more and more problems arising from the poor practices of the past and present, ground water issues are quickly becoming a visible part of our lives and of concern to everyone.

SCS Applications and Objectives

The objectives of this manual are to present the basic principles of ground water and to illustrate various ways in which this information may be realistically applied under everyday circumstances. Little emphasis will be put on describing the ground water conditions in all 50 states—that would be of little use to you on a specific regional basis. Although the science of ground water is one which is quantitative, concepts here will not be presented with long formulas or equations. The intent is to provide you a common sense sort of knowledge of ground water so that you can answer some basic questions, make some informed decisions, perform some basic investigations and to recognize when a problem requires the skills of another professional. Most importantly it will enable you to understand the basics of ground water within your particular region and perhaps dispel some of the long-believed myths about ground water. We don't expect a soil conservationist to solve hydrogeologic problems overnight, but with a better understanding of the basics they can be a valuable first link in the process.



Explanation

Area problems

Significant ground-water pollution is occurring

Salt-water intrusion or ground water is naturally salty

High level of minerals or other dissolved solids in ground water

Unshaded area may not be problem-free, but problem was not considered major

Specific sources of pollution

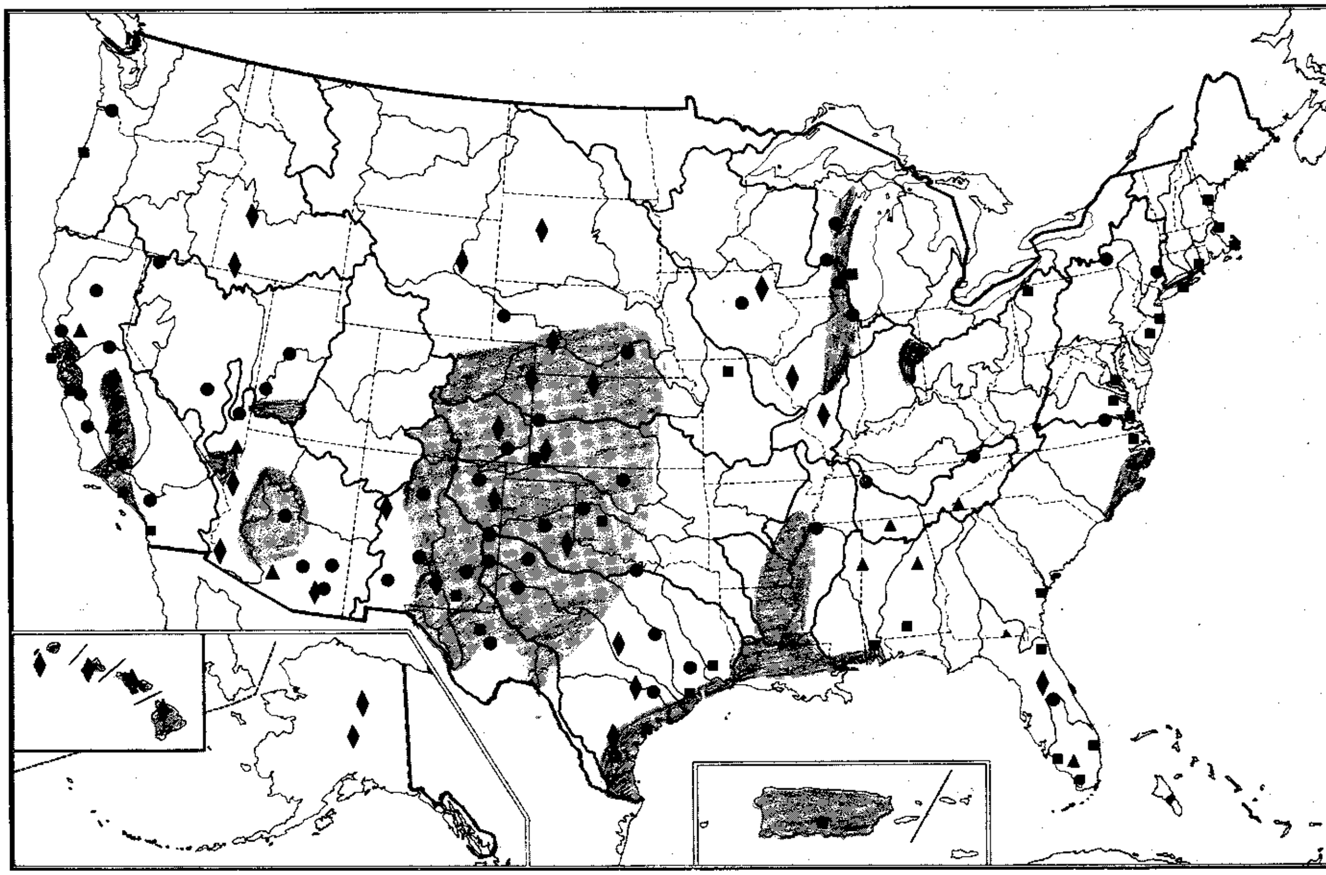
- ● Municipal and industrial wastes including wastes from oil and gas fields
- ♦ Toxic industrial wastes
- ▲ Landfill leachate
- ■ Irrigation return waters
- Wastes from well drilling, harbor dredging, and excavation for drainage systems
- ★ Well injection of industrial waste liquids

Boundaries

Water resources region

Subregion

Figure 1-1. ***Ground water pollution problems (as identified by federal and state/regional study teams).***



Explanation

Area problem

Area in which significant ground-water overdraft is occurring

Unshaded area may not be problem-free, but the problem was not considered major

Specific problems *(as identified by Federal and State/Regional study teams)*

● Declining ground-water levels

♦ Diminished springflow and streamflow

▲ Formation of fissures and subsidence

■ Saline-water intrusion into fresh-water aquifers

Boundaries

Water resources region

Subregion

Figure 1-2. *Ground water overdraft and related problems (U.S. Water Resources Council, 1978).*

Your instructor will tailor this material to the specific conditions in your area by using regional examples and references.

The actual number of ground water concepts is small and extremely global. In reality, ground water moves through a Texas sand the same as it does an Ohio sand. When the general concepts are combined with the specific regional or local factors such as terrain, soil, surface water, climate, geologic setting, and human activity, complex situations can occur. You already understand many of these factors in your region. Now you need to see how they relate and interact with the ground water.

Scope

General Definition of Ground Water and Aquifer

Ground water is the water found below the surface of the earth and which fills the pores, voids, and fractures within soil and rock. When a mass of soil or rock is capable of storing and yielding a usable amount of water to the surface it is called an aquifer.

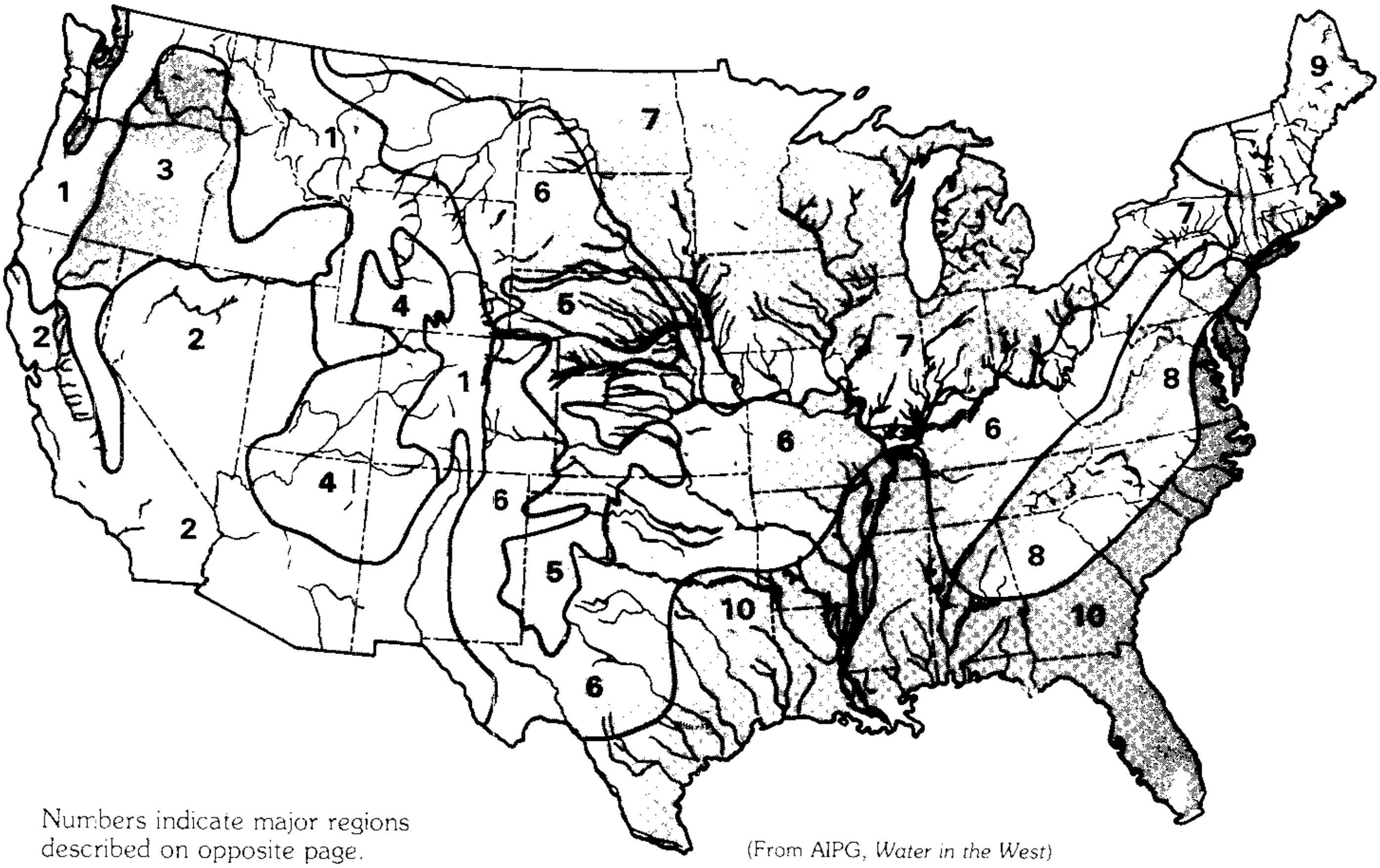
An aquifer is like a sponge: a semi-rigid structure surrounding a maze of internal open spaces. When the sponge is immersed into water those open spaces naturally fill with water. An aquifer acts the same way.

When our soil conservationist, Mike Kenton, was a boy his father used to tell him about the underground river that flowed under Jefferson City. He and many other people used to picture a cavernous corridor filled with water, flowing under the city and following the Little Kuma River until it reached the ocean. In many minds that picture of ground water still exists, to the point where the basics of underground flow are misunderstood. True, there are some karst aquifers where the solution of solid rock has opened underground channels through which water flows, just as it does in a pipe, but the majority of aquifers are composed of a porous material through which water is able to move in a much more diffused way. In most cases, the directional movement is not nearly as well defined or predictable as that of a surface stream. So, if you're a believer in "underground rivers", relax that concept for a while. It tends to put too many limits on some of the concepts that follow. Back to aquifers!

Aquifers can be composed of consolidated or unconsolidated materials. Unconsolidated formations of soil, sand, and gravel contain varying amounts of open void space between the individual particles. If these materials are below the water table, they can contain large amounts of water. Consolidated masses of rock such as limestone, dolomite, and sandstone can hold and carry ground water in cracks, fractures, and solution channels. Even dense igneous rocks such as basalt and granite can transmit water through joints and fractures. This is not to say that any formation that can hold water makes a good aquifer. It's not so much the amount of space within the material that matters, but the size of the spaces and the way in which they are connected. The amount of pore space within a given amount of clay can be enormous and it may be able to hold a great amount of water, but all of you probably know how difficult it is to drain a clayey soil. A real problem! On the other hand water can readily move through a clean gravel. So another important characteristic of a good aquifer is the ability for ground water to move through it. More about this later.

The volume and shape of an aquifer can vary considerably. It can be capable of producing from just a few gallons to billions of gallons of water per day. An aquifer may be a small closed system beneath someone's backyard or a continuous aquifer system covering many states. It can be long and slender and have definite boundaries like a buried valley aquifer or spread out in all directions with no apparent boundaries. Some areas of the country have productive aquifers, some don't have any at all and must rely on surface water supplies. The map on figure 1-3 shows the distribution of the major aquifers across the country.

Just one more thing. There is a problem in talking about good and bad aquifers: what may be good in one set of circumstances may be not so good in others. For instance a clean sand or gravel aquifer zone is extremely desirable in the case of a municipal water supply well. That same porous zone, however, can be the worst thing in the world when a toxic contaminant is quickly on its way to the pumping well. Even the best aquifers can turn into deadly enemies by quickly delivering contaminants to the water user. So , the perspective of a well driller interested in producing water can be quite different from that of a geochemist trying to track down the source of a specific contaminant. A soil conservationist's thinking may often need to range between the two extremes. It all depends on the specific situation.



Numbers indicate major regions described on opposite page.

(From AIPG, *Water in the West*)

Watercourses related to aquifers

Areas of extensive aquifers that yield more than 50 gallons per minute of fresh water

Areas of less-extensive aquifers having smaller yields

Ground water sufficient for domestic and livestock supplies can be found throughout the country.

Larger ground-water supplies for industry, municipal use, and irrigation are obtained from high-permeability rocks and river deposits (alluvium).

Groundwater Resources in Geologic Regions

1. Western Mountains
2. Alluvial Basins
3. Columbia Lava Plateau
4. Colorado Plateaus and Wyoming Basins
5. High Plains
6. Unglaciated Central Region
7. Glaciated Central Region
8. Unglaciated Appalachians
9. Glaciated Appalachians
10. Atlantic and Gulf Coastal Plains

Figure 1-3. ***Ground water resources in the U.S.***

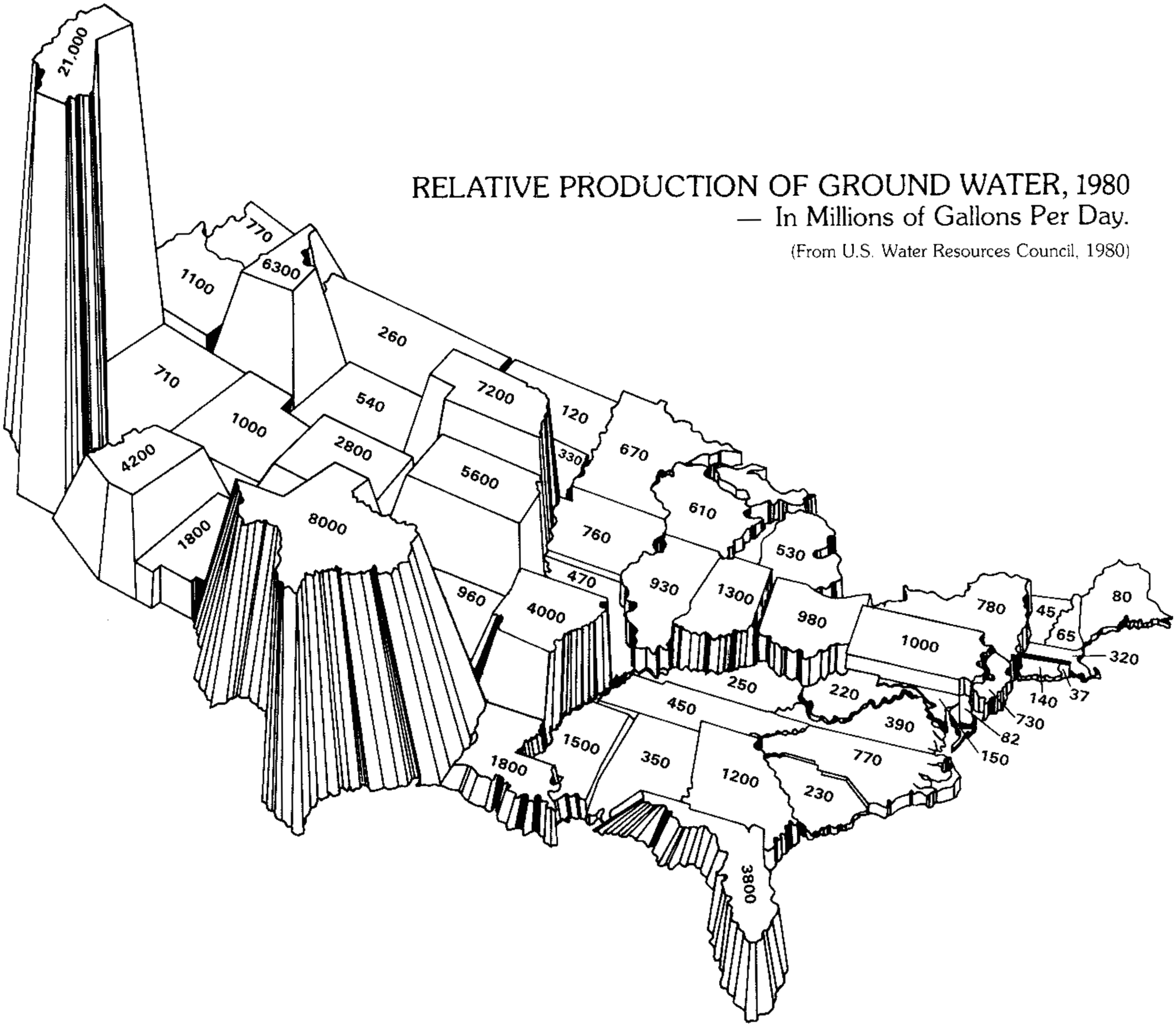
Basically, if an aquifer yields enough water of acceptable quality to the user, be it two or two thousand gallons per minute, it's a good one.

Ground Water Use

The United States Geological Survey has estimated that a total of 89 billion gallons of ground water is used in the United States everyday. Approximately 12 billion gallons per day (bgd) is used as public drinking water, another 64.5 bgd goes toward irrigation and rural use (drinking water and livestock) and the remaining 12 bgd is used for industrial purposes. Figure 1-4 shows a comparison of ground water production in the 50 states. Figure 1-5 shows a comparison of surface and ground water uses and trends in the United States from 1950 to 1980.

Specific Regional Usage Patterns and Aquifer Regimes

Depending upon the level of development and types of activity within a region the degree and variety of ground water use may vary significantly. As one might expect, the use of ground water for irrigation in the western states far exceeds that of the eastern states. Of the total amount of ground water used in irrigation, 80 percent of it is used in 17 western states. Almost 84 percent of the total industrial use of ground water is in 31 eastern states.



- ☐ Although ground water is the main source of rural water supplies, and is the source for many cities, those uses are relatively small compared to irrigation demand. *Irrigation accounted for about 70% of the ground-water production in 1980.*
- ☐ Ground-water production for irrigation *tripled* between 1950 and 1980, increasing from 20 to 60 billion gallons per day.
- ☐ Irrigation demand, and thus the largest ground-water production, is concentrated in the semi-arid western states and in Florida.
- ☐ The four leading ground-water pumping states — California, Texas, Nebraska, and Idaho — account for almost *half* the total national production of ground water.

Figure 1-4. ***Distribution of ground water use.***

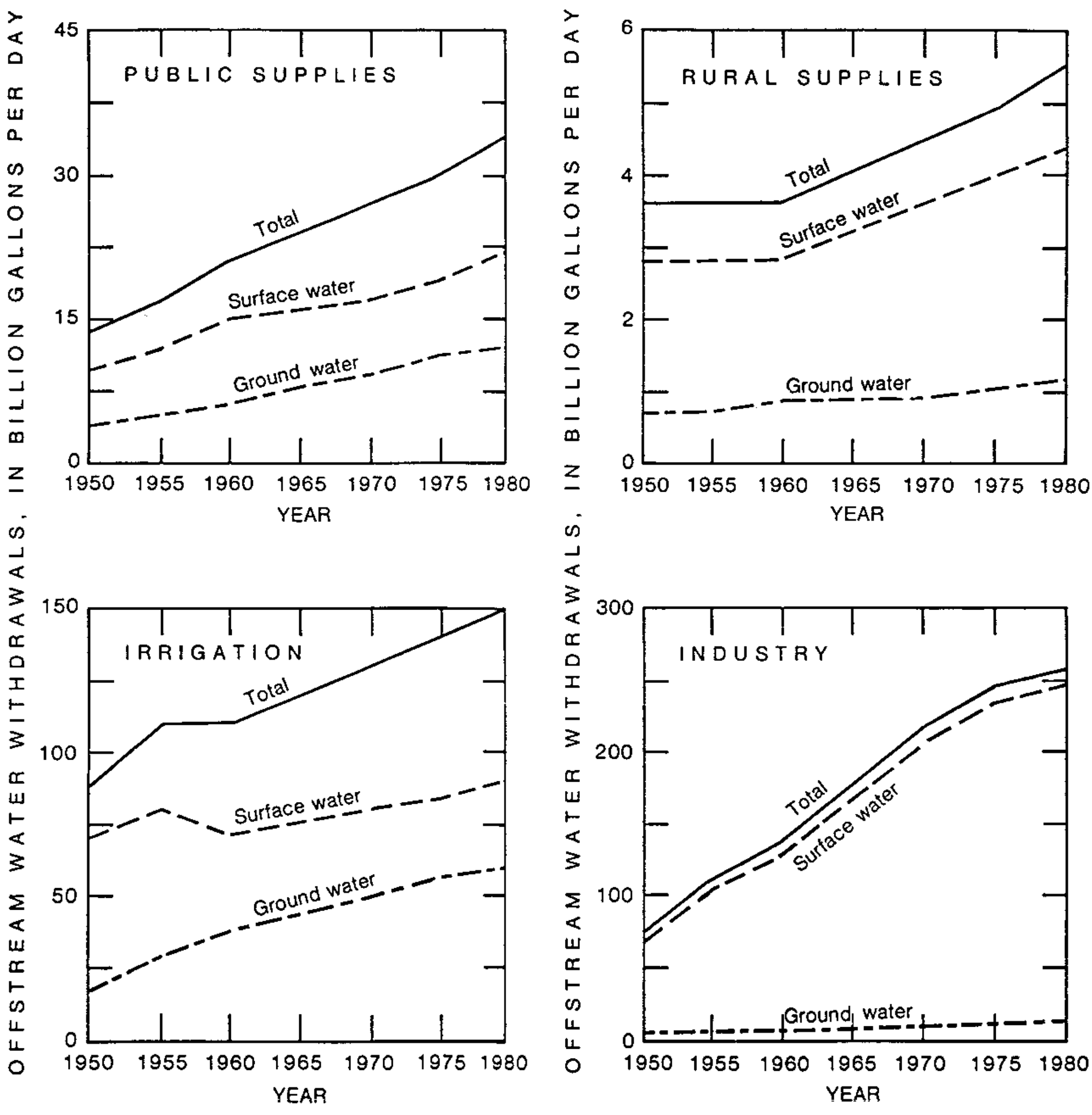


Figure 1-5. ***Trends in water withdrawal for public supplies, rural supplies, irrigation, and self-supplied industry, 1950-80. (source : U.S. geological survey).***

II. Introduction of Case Study

To illustrate how some of the basic principles of ground water may be applied to real world circumstances, information from an actual case study will be used. This community is currently dealing with some typical and potentially serious ground water questions. We'll change its name, some of the environmental factors surrounding it and then add some extra ground water and geologic factors from other cases, just to make things interesting. So the main case study doesn't get too complicated, examples from other places will be used to illustrate a few of the less typical conditions.

Statement of Problem

As brought to light in the introduction of this manual the evidence suggests that the Jefferson City water supply is being contaminated by pollutants from an unknown source or sources. There have been other minor incidents of soil and ground water contamination in Jefferson City previously; however, this is the first time that possible health threatening substances have been involved.

Over the past few decades, there have been many activities and land uses in the Jefferson City area that may have involved tens if not hundreds of potentially environmentally threatening substances. There is no way you can account for all the possibilities involved. The most effective way to find the source of the contamination is to start at the point of detection and work your way backward through the system. This will require a fair amount of detective work: gathering clues, piecing them together and making some interpretations. The ground water system is composed of a series of cause and effect relationships. To solve the problem you must first understand this system. This understanding does not need to be on a highly quantitative or scientific level. A solid, conceptual, common sense sort of knowledge of the local conditions can go a long way toward unravelling the most complex ground water puzzles.

Keep in mind that our main purpose in using this case study is to illustrate basic ground water concepts. While finding a specific contamination source is, in reality, the prime objective here, the thought process involved in coming to that point is of greater concern.

Description of Study Area

Background

Welcome to Jefferson City. The town was first established in 1806 on the inside of a large meander of the Little Kuma River by trapper and trader Finneus Jefferson. Located at the intersection of this north-south flowing river and a major east-west trail during the 1800's, Jefferson City was a major point of trade between the Great Lakes to the north, the industrial states to the east and the expanding west. The Little Kuma River also is a tributary to the Mississippi River, which was an important connection to the lower midwest and south in those days. During the early to mid 1900's the city was primarily known as a regional agricultural center and for its two or three major industries.

With the increased growth of a major metropolitan area about 30 miles to the south and the proximity of major interstate and railroad routes, there has been a significant increase in commercial and industrial activities in Jefferson City during the past 20 years. This accelerated growth has resulted in extensive development of all types, both within the city and along its fringes.

Jefferson City currently has a resident population of 35,000. The city is the county seat of Kuma County and has two high schools, seven churches, a hospital, a fairgrounds, several municipal parks and a country club.

Figure 2-1 presents a base map which shows the major boundaries, locations, landmarks, industries, transport routes and land uses, which may be referred to in the following sections.

Topography

The land surrounding Jefferson City can best be described as a flat to gently rolling glaciated terrain. The Little Kuma River forms a large wide floodplain 2 miles across at its widest point. The river valley floor is at an approximate elevation of 850 feet above sea level with the surrounding uplands rising to 950 to 1000 feet above sea level. The general topography of this case study area is on the map in figure 2-2.

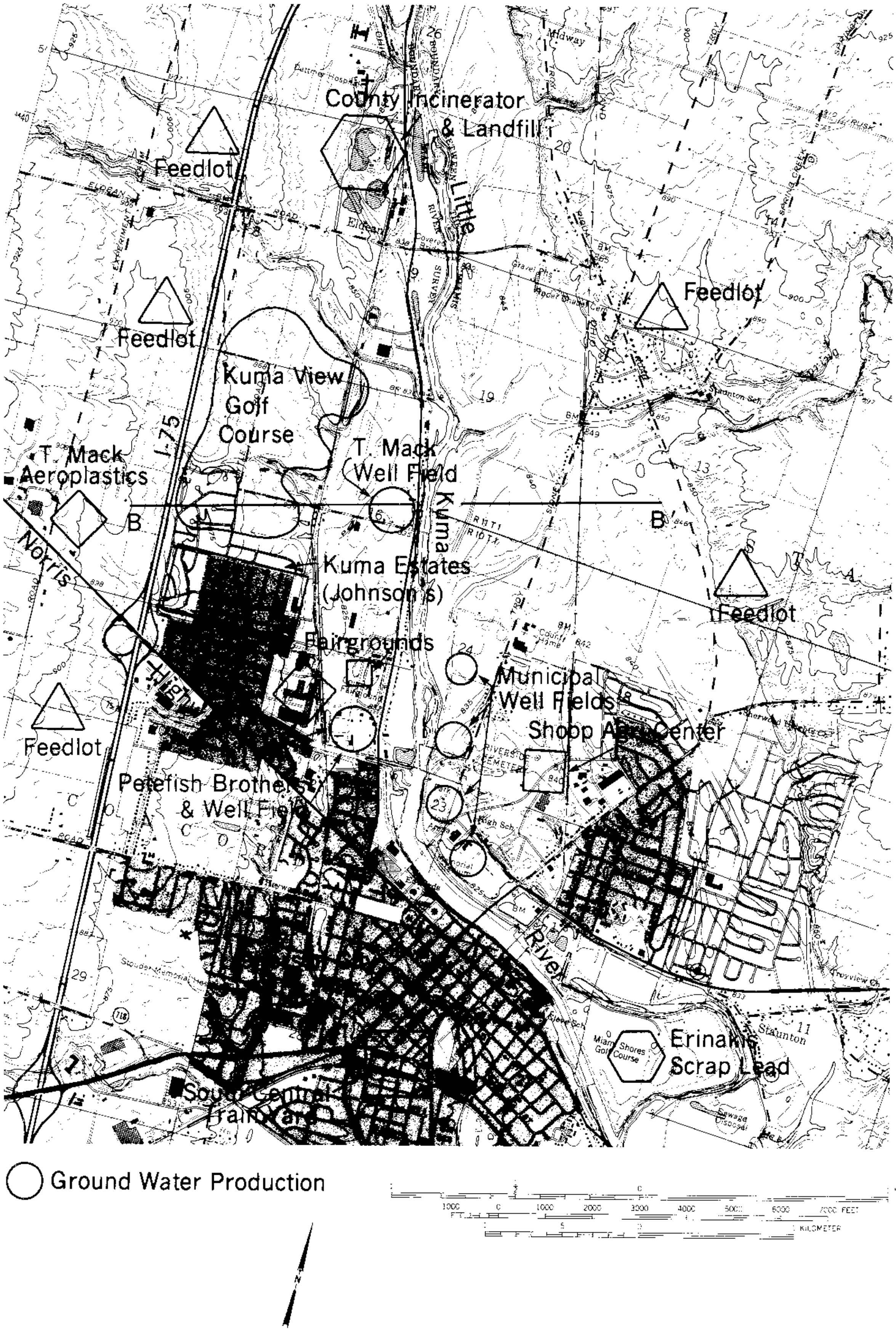


Figure 2-1. *Jefferson City landmarks.*

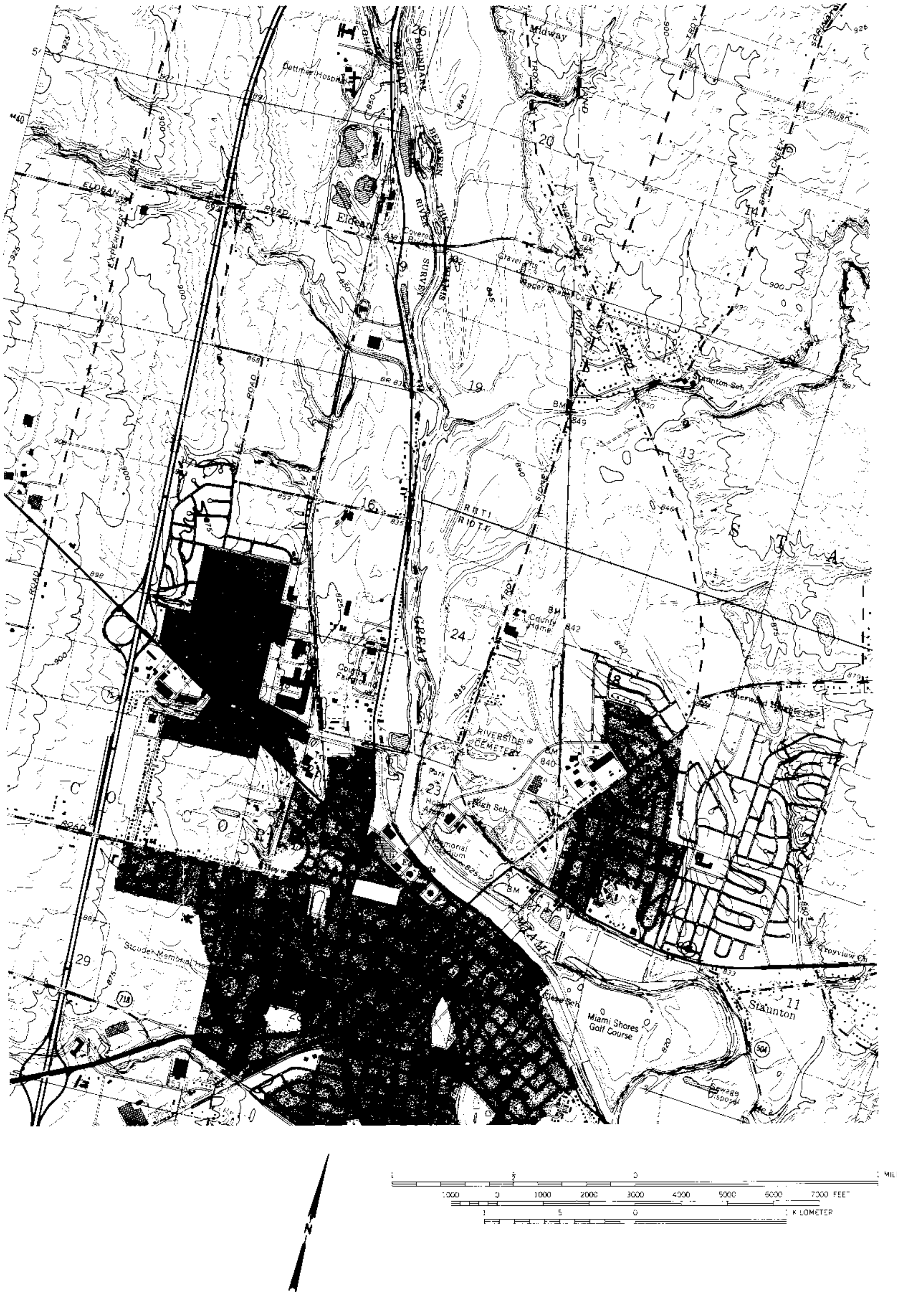


Figure 2-2. *Jefferson City topography.*

Soil

The soil types within the study area are all derived from various glacial materials that underlie them. The map in figure 2-3 shows the major soil descriptions and their distribution.

Hydrogeologic Setting

Unconsolidated Materials. More than 200 thousand years ago in this region, there was a large river that flowed from north to south. This river was much bigger than the present day Little Kuma River and was able to erode a broad deep valley into the shale and limestone bedrock of the region. With the onset of glaciation, an enormous amount of unconsolidated material was transported by ice from areas north in Canada. There were several episodes of glaciation during which continental glaciers inched across the area. Upon the retreat of these ice masses a great amount of material was deposited either directly from the ice or by its meltwater. The material deposited directly from the ice was an unsorted mixture of clay, silt, gravel, sand, and boulders and is known as till. The non-uniformity of this material makes it a poor aquifer material. On the other hand, the material deposited by the huge amounts of water pouring off the trailing edges of the glaciers was well sorted by the high energy water. These materials are called outwash materials and have favorable aquifer characteristics. Many of these outwash materials were deposited in the valleys along major drainage routes. These sequences of sand and gravel are known as valley train deposits. With each advance and retreat of the ice masses, the previous landscape was gradually altered and the pre-existing drainage routes were filled. When glaciation ceased, the previous stream valleys were left buried beneath the present landscape.

Underlying the present day Little Kuma River Valley is a buried valley filled with a mixture of valley-train and till deposits. This buried valley aquifer is capable of storing and transmitting vast amounts of ground water. The general route of this ancient buried river valley is best indicated by the present day route of the Little Kuma River that flows above it. The map in figure 2-4 provides the elevation contours of the bedrock surface and the general boundaries of the buried valley.

The Little Kuma River buried valley is broad and deep with the remnants of a deeply incised V-shaped drainage channel meandering across its floor. This channel is evidence of a high energy environment that means the sediments filling it are well sorted and capable of yielding relatively greater amounts of water than the other surrounding aquifer materials. The total thickness of the valley fill material at these points is about 300 feet. The average thickness of the valley fill materials ranges between 200 and 250 feet.

The sequences of till and outwash materials in the subsurface are complex. Figure 2-5 is a geologic cross-section across the buried valley in the study area, which illustrates the valley fill relationships. One should note that in some places there are two major aquifer zones composed of sand and gravel, which are separated by a semi-continuous layer of variable thickness till. In some areas there may be more than two aquifer zones.

The uplands above the topographic valley are composed predominantly of sandy till, which was laid down directly from the ancient ice masses as ground moraine. There also are remnants of buried stream channels and moraine deposits, composed of varying amounts of glacial sand and gravel, which dissect this upper surface and, in some cases, actually drape over the valley wall and connect with the buried valley aquifer.

Consolidated Materials. The underlying bedrock in this region is predominantly composed of shale that has some thin sequences of limestone. These materials are extremely impermeable and are not capable of transmitting or yielding significant amounts of ground water. For this reason the bedrock will be thought of as the outer limit or boundary for ground water movement. There is relatively little ground water entering or leaving the system through bedrock routes.

Ground Water Use

Jefferson City and the surrounding area are dependent upon ground water for nearly all domestic, rural, commercial, and industrial needs. The main source for the ground water supply is the buried valley aquifer beneath the Little Kuma River. The Jefferson City municipal supply comes from production wells in Norris Community Park along the east side of the river. The total production from these wells averages 5 million gallons per day and serves two thirds of the city's population and a good deal of the industrial use. The rest of the population, living in older parts of the city and in the unincorporated suburbs, obtain their water from private water wells. The total private well production from the

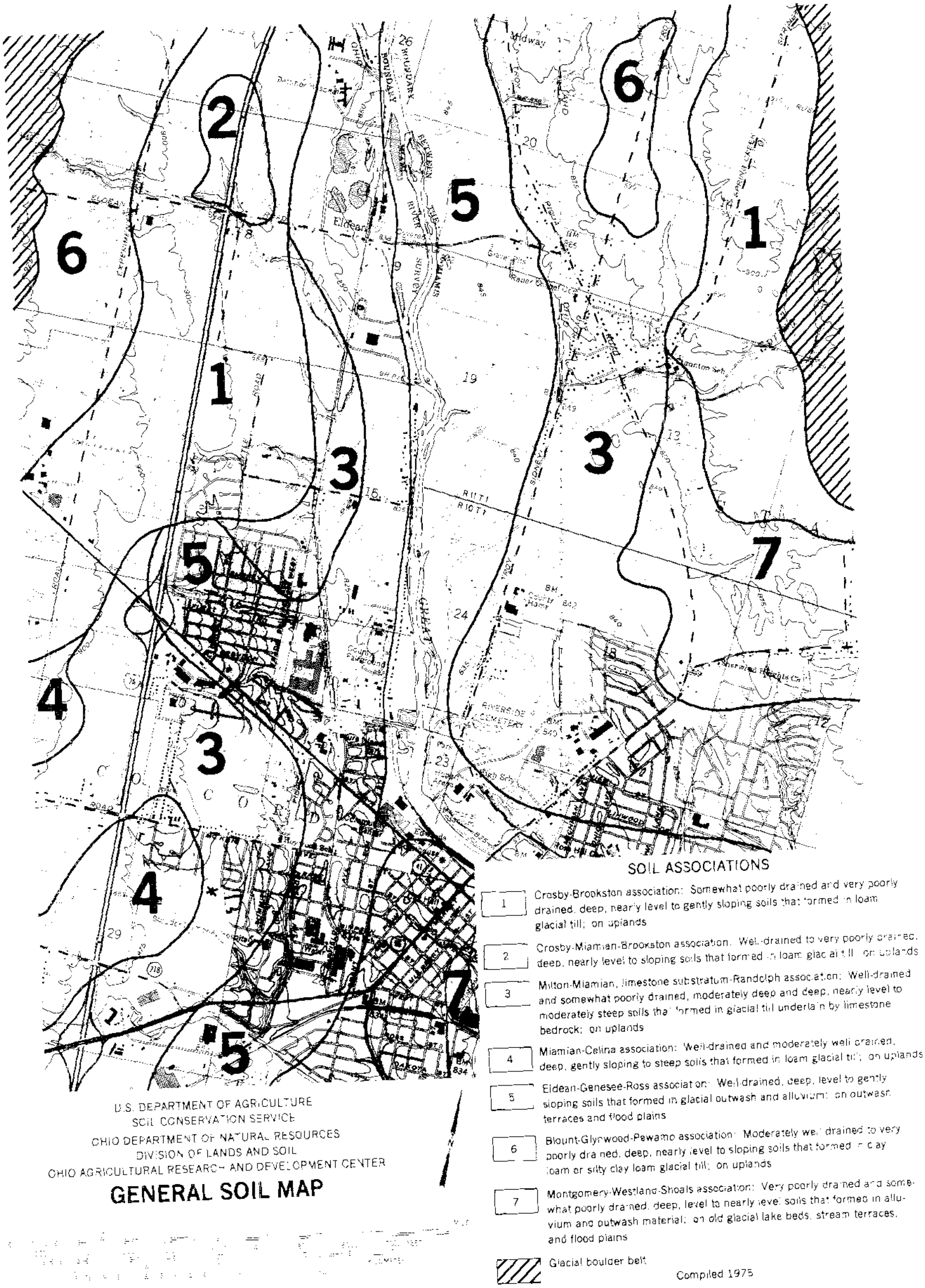
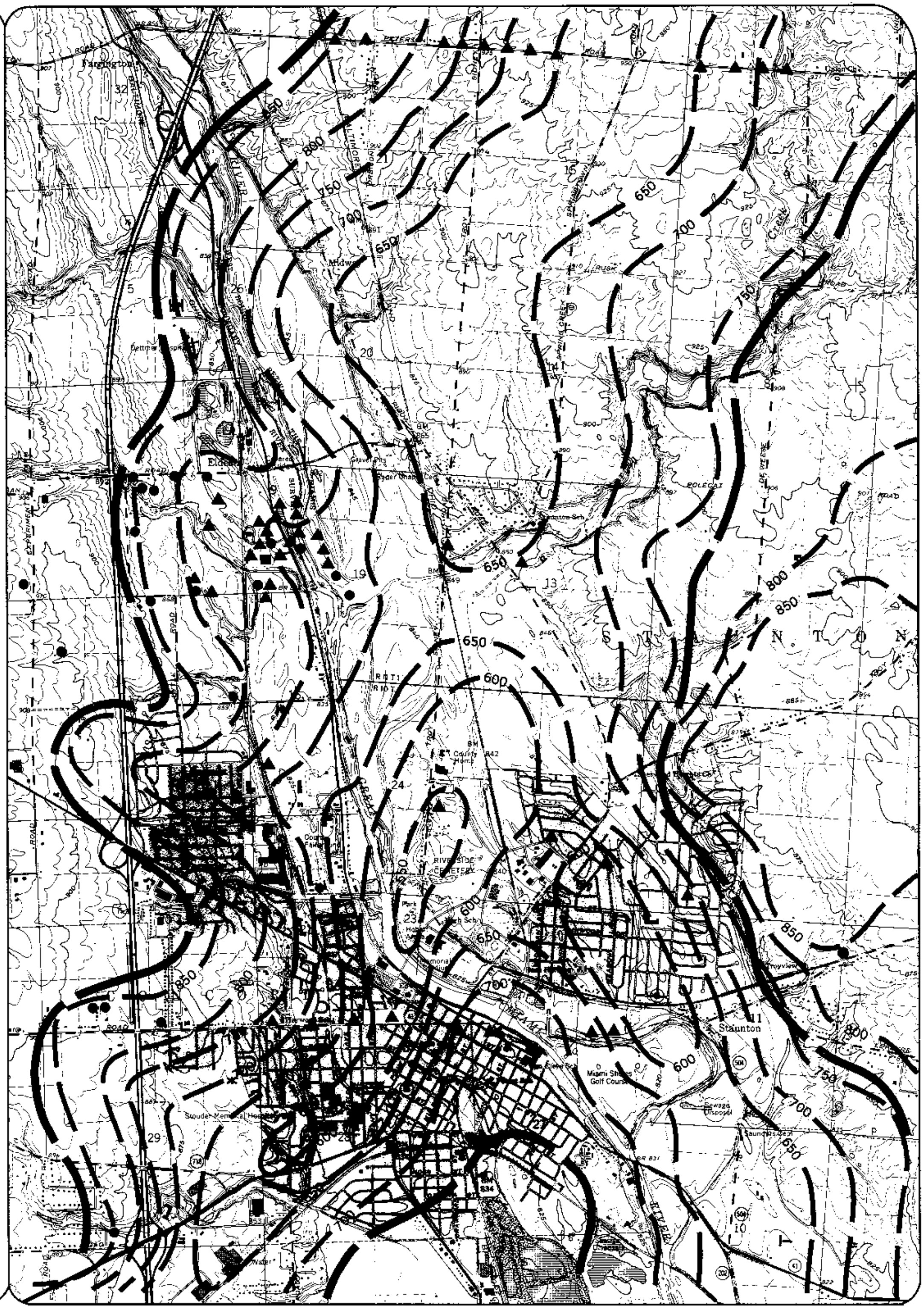


Figure 2-3. *Jefferson City soil map.*



● Bedrock elevation from well data

▲ Bedrock elevation estimated from geophysical data

— 850 — Bedrock elevation contour line

Contour interval = 50 feet

▬▬ Buried valley boundary

N

Figure 2-4. *Jefferson City bedrock contour map.*

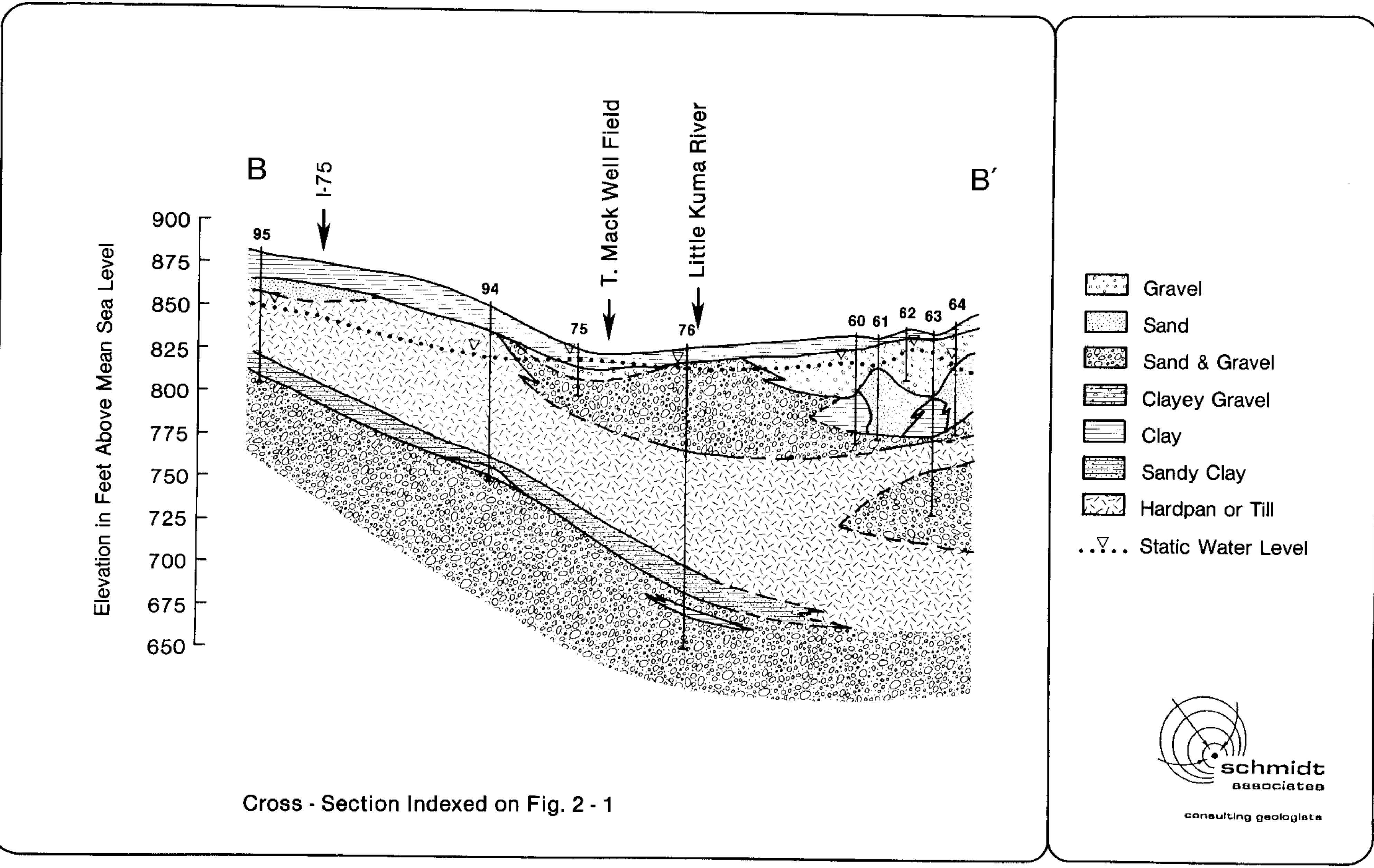


Figure 2-5. ***Generalized subsurface cross-section across the Little Kuma River valley.***

area above the buried valley amounts to about 1.2 million gallons per day. Almost the entire Jefferson City supply, whether from public or private sources, comes from the buried valley aquifer.

Two of the major industries, T. Mack Aero Plastics (which is actually located outside of the buried valley, but maintains a pipeline to its own wells along the Little Kuma River) and Petefish Brothers Incorporated, both extract large amounts of water from the buried valley aquifer to use in their manufacturing processes. Together they produce about 2 million gallons per day.

The locations of major ground water production facilities are indicated on the map in figure 2-1.

Waste Disposal

Within the Jefferson City corporation limits, public sewerage is provided. The city's sewage treatment plant is located on the southeast side of town. Dwellings not hooked into the public system have their own septic systems.

Just north of Jefferson City is the county incinerator. This facility is located on the site of a previous solid waste landfill. The landfill was originally established in one of the many gravel pits excavated into sand and gravel along the perimeter of the Little Kuma River valley wall. This landfill is now closed with the exception of accepting ash from the incinerator operation. There has long been concern regarding the possible contamination of the private and municipal wells located down gradient from this site.

South of the city is Erinakis Scrap Lead Inc., a company involved with the separation and recycling of lead from old automobile and industrial batteries. (Their company slogan is, "We get the lead out.") Once separated, the usable lead is sold, and the spent battery casings and wastes are buried at the site. Monitoring activities have been conducted around this site by the EPA and show elevated levels of lead in the ground water.

Chemical Characteristics of the Ground Water

The study area is underlain by predominantly carbonate-rich bedrock. Naturally occurring water tends to reflect the chemical environment which surrounds it. It follows then that the ground and surface water in the Jefferson City area is high in calcium and bicarbonate. This is typically referred to as "hard" water. The ground water is about average in other chemical constituents such as silicon, sodium, potassium, magnesium, chloride and manganese. Concentrations of iron are high in the study area and it has high levels of sulfur and nitrates in certain localities. The ground water is alkaline with pH's ranging between 7.2 and 7.8. Figure 2-6 shows the ranges for the natural ground water constituents in this region.

Methodology

A systematic approach is commonly used in dealing with ground water problems, regardless of what they may be. The initial goal is to understand the setting in which the problem is occurring. To fully understand the setting you must first do three things:

1) Identify and quantify the separate elements interacting in the system.

2) Define the scale and boundaries of the system.

3) Define how the specific system reacts and handles natural and artificial changes exerted from both inside and outside of the system.

Gaining an understanding is a little like managing a business. Let's say a farm. If you wanted to run a farm you certainly wouldn't buy one unless you already knew something about farming (although a few folks have!). You'd need to have some basic knowledge of what goes into operating a successful farm: labor, livestock, machinery, crops, sun, water, good soil, a little luck, etc. Knowing that, you've defined the basic elements that will be interacting on your farm.

Once you've bought the farm and are settled, you then must decide how you're going to use the various types of land. Each type has its own strengths, weaknesses and limitations. During this process you establish the boundaries for the

Constituent	Concentration mg / l
Chloride	10.20
Sulfate SO_4	45.00
Nitrate Nitrogen NO_3^{-N}	<1.00
Ammonia Nitrogen (NH_3)	<0.50
Cadmium	<0.01
Lead	0.02
Calcium	80.00
Magnesium	35.00
Sodium	29.00
Potassium	2.20
Iron	0.09
Manganese	<0.01
Alkalinity (to pH 4.5 as $CaCO_3$)	280.00

Figure 2-6. ***Constituent ranges in Jefferson City ground water.***

various activities in which you're going to be involved. For example, you know that the cattle are not going to be routinely grazing in the corn or wheat fields and that you must keep your plow clear of that little swampy area in the lower forty. Eventually you get a feel for the boundaries and limitations of the system.

The most important part comes later with a little experience. That's the part where you've invited all your friends out to the place for a pig roast. Suddenly, the wind direction changes for the first time since you've been there, and brings the fragrance of that manure (which you just spread out in the field yesterday) floating over your guests' potato salad! The system is reacting to change. Question: Were you thinking about how a change in the wind would affect your upcoming get-together when you were spreading that manure? Maybe next time you will! Odds are that the longer you work the farm, the more you'll understand it, and the better you'll become at predicting how it will respond to your actions. (Twenty or thirty years ago, if more people would have considered how their actions would be affected by time and changing conditions, many of our resources, especially ground water, would perhaps not be threatened today.) Understanding how the system reacts to change is important.

The methodology outlined above is the same one used in understanding ground water systems. One has to first identify and measure the elements going into and coming out of the system. How much water enters the system and how much leaves it? Next you need to understand the boundaries and scale of the system. What kind of aquifer is it? How big is it? Does it have boundaries and if so what and where are they? Next you need to determine the path of ground water flow through the system and whether or not this path coincides with any potential threats. In other words get a feel for how the system deals with specific natural or manmade factors. Once these basic questions are answered you will have the basic tools necessary to make some accurate predictions and often exert some control over the system.

The next chapter describes the more significant elements interacting within a ground water system: precipitation, evaporation, transpiration, infiltration, runoff, baseflow, stream flow, and recharge.

III. The Hydrologic Cycle

Ground water is one sub-system of another larger system known as the hydrologic cycle (fig. 3-1). This cycle consists of the many pathways a particle of water may take on its journey from the sea to the atmosphere to the land and ultimately back to the sea. In this cycle there is no point of beginning or ending and there are an infinite number of pathways. A particle of water may complete the entire cycle or be forever caught up in one or more of its smaller sub-cycles.

Figure 3-1 shows a general representation of the hydrologic cycle.

Earth's Water Regimes

The earth's water is everywhere in one or more of three basic forms: liquid, solid or gas. As a liquid it makes up the world's oceans, lakes, streams, ground water and living things. In a solid form it appears as the snow and ice that make up glaciers and the polar icecaps. As a gas it resides in the atmosphere as water vapor.

Depending on the type of regime, water may stay in a form just a few days to thousands of years. Turnover time is the amount of time that a volume of water resides in an environment before it is replaced by a new volume of water. For river water this turnover time is about 2 weeks; whereas ground water has a relatively longer turnover time, usually from tens to thousands of years. When ground water supplies are recycled at such slow rates, one can easily understand why there should be concern over protecting them.

Elements of the Hydrologic Cycle

The hydrologic cycle is made up of several different elements. Here the cycle is divided into eight different parts:

1) Precipitation
2) Evaporation
3) Transpiration
4) Infiltration
5) Surface Runoff
6) Base Flow
7) Stream Flow
8) Storage/Recharge

Each one will be defined and discussed briefly. Just remember, although there are many other ways and terms that are used to define and classify these elements, it always boils down into the same interrelated system.

Precipitation

Precipitation is the process by which water vapor condenses into the atmosphere or onto a land surface in the form of rain, sleet, snow or dew. This condensation is brought about when a moisture laden air mass is cooled. This cooling most often takes place when the air mass is forced to rise by any one of three factors: frontal movements, where an intruding, colder air mass forces warmer, moister air upward; convective currents in the atmosphere, caused by air rising from a heated land surface; or orographic effects brought about by irregularities in the land surface (fig. 3-3 a, b and c). Perhaps the most important thing to note about precipitation is its intensity and duration. During a short heavy downpour of rain, the soil may be dry and have room for a large amount of water, but the intensity of the rain may be so great that little of the rain enters the soil and actually runs off or stands on the land surface. Prolonged periods of moderate steady rain are much more likely to result in water entering the soil and subsequently the ground water zone. Rainfall tends to be of longer duration and of less intensity in humid regions as compared to more arid regions where a large amount usually falls during a relatively short period of time.

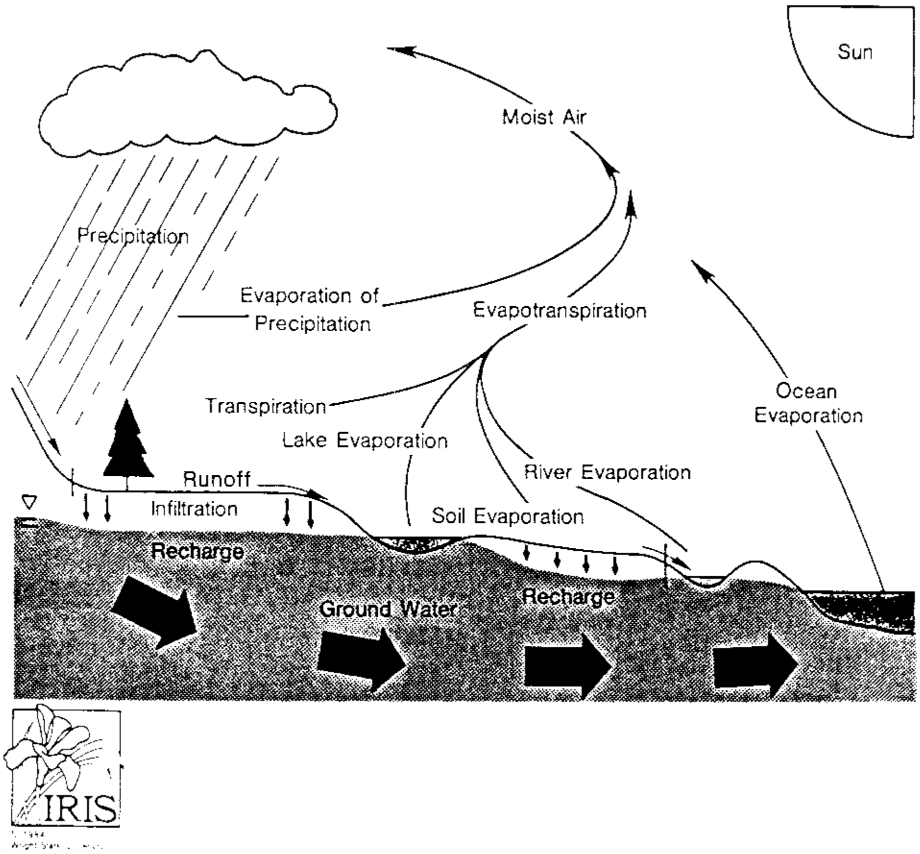


Figure 3-1. *Hydrologic cycle.*

Parameter	Volume (km³) X 10⁶	Volume %	Surface area (km²) X 10⁶	Residence time
Oceans and seas	1370	94	361	~ 4000 years
Groundwater	60	4	130	2 weeks - 10,000 years
Icecaps and glaciers	30	2	17.8	10 - 1,000 years
Lakes and reservoirs	0.13	<0.01	1.55	~ 10 years
Soil moisture	0.07	<0.01	130	2 weeks - 1 year
Atmospheric water	0.01	<0.01	504	~ 10 days
Swamps	<0.01	<0.01	<0.1	1-10 years
River channels	<0.01	<0.01	<0.1	~ 2 weeks
Biospheric water	<0.01	<0.01	<0.1	~ 1 week

Figure 3-2. ***Water balance of the world.***

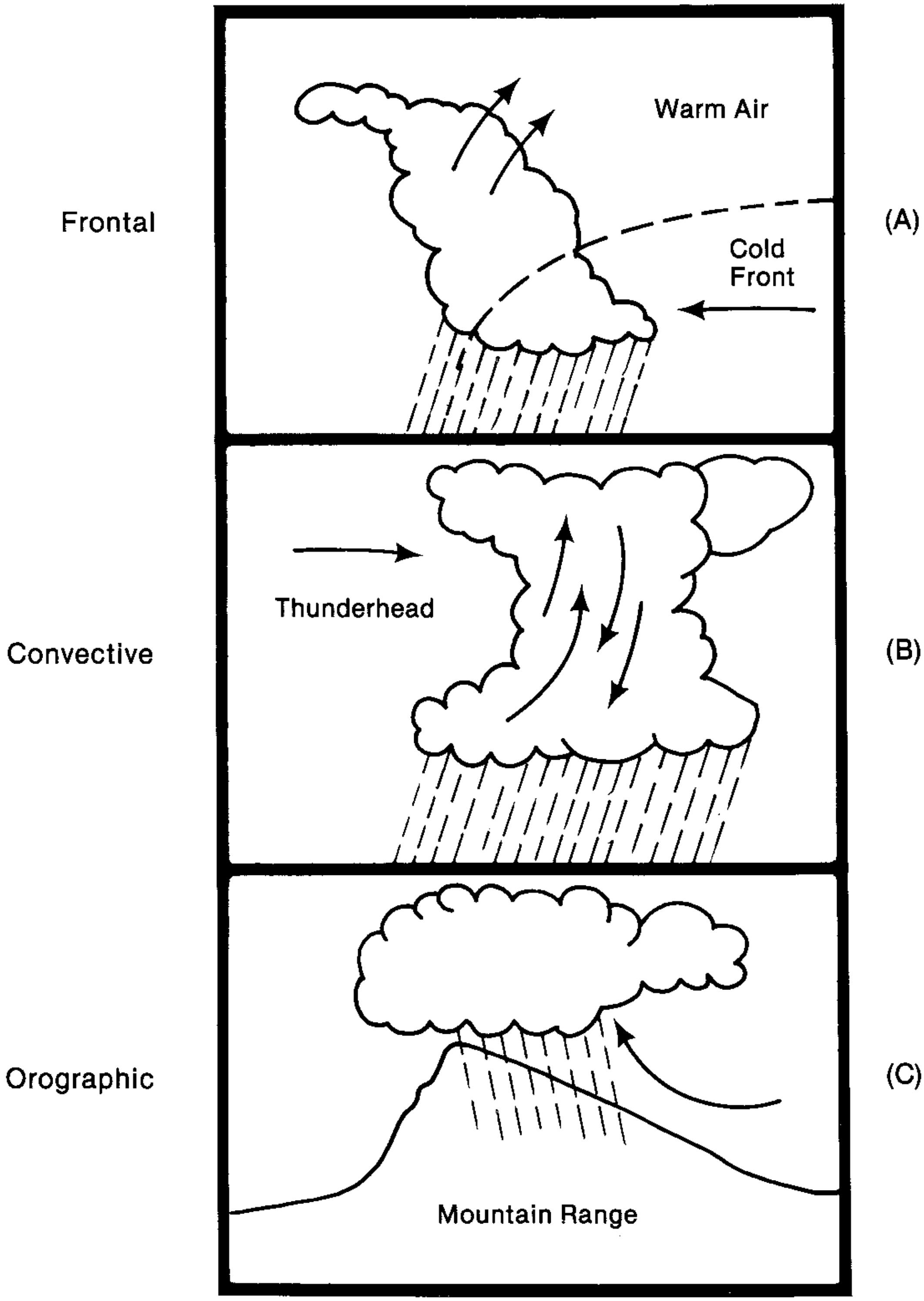


Figure 3-3. *Precipitation mechanisms.*

Evaporation and Transpiration

These processes, evaporation and transpiration, are often discussed together because they are difficult to separate and quantify under field conditions. In hydrologic studies the combination of these two processes is referred to as evapotranspiration.

Depending upon a variety of atmospheric and climatic factors a portion of the precipitation that falls to the earth's surface will return directly back to the gaseous state through the process of evaporation. Evaporation from land and water surfaces is an important consideration when attempting to quantify the amount of ground water available within an area. The greater the surface area, whether it be land or water, the greater the potential for evaporation to take place. A large amount of precipitation in an area could lead one to believe that an excess of ground water may exist, when in reality, the majority of precipitation may be evaporating back to the atmosphere. Some precipitation evaporates back into the atmosphere before it ever strikes a land or water surface.

Plants are also responsible for returning water directly back to the atmosphere through the process of transpiration. Water in the root zone is taken up by plants, a portion is used to manufacture plant tissue, and then as much as 99% is returned to the atmosphere through the leaf surfaces. Transpiration accounts for the majority of water lost to the atmosphere from land surfaces. The size and density of the vegetation governs the amount of transpiration that can take place.

Certain types of plants, such as cactus, in arid and drought prone climates are especially adapted to minimize transpiration loss. These plants are called xerophytes and are characterized by shallow root systems that are adapted to make the most of low soil moisture conditions and by modified leaves that reduce transpiration and conserve water in the plant tissue. Other plants, known as phreatophytes, have deep tap root systems that extend below the water table and are capable of transpiring enormous quantities of water back into the atmosphere. Common phreatophytes include willow, cottonwood, saltgrass and mesquite. These types of plants are often surface indicators of ground water discharge areas and will be discussed later. The comparative relationship of these two plants to the ground water zone is in figure 3-4.

Infiltration

Infiltration occurs when water flows downward from the land surface and into the soil. Infiltrating water may pass through two distinct zones. The first zone is termed the unsaturated or vadose zone and is defined as the zone below the ground surface in which the pore spaces are only partially filled with water. Beneath this zone lies the saturated or phreatic zone where all the pore spaces are filled with water. The top surface of the zone of saturation is called the water table. The water in the vadose zone above the water table is called soil water or interstitial water. Water in the phreatic zone below the water table is called ground water. Recharge occurs when surface water infiltrates through the soil and into the saturated zone. Between the saturated and unsaturated zone there is a transitional zone called the capillary fringe. The capillary fringe results from the attraction between water and the soil and rock particles. This attraction causes water from the saturated zone to adhere to the surfaces of these particles and rise in small diameter pore spaces against the force of gravity. Figure 3-5 is a diagram of the vertical zones.

Each soil has a finite capability for allowing water to infiltrate into it. This infiltration capacity depends upon the kind of soil and the amount of moisture present. A dry soil would have a relatively high infiltration capacity. Capillary forces between water and soil particle surfaces act to draw water into the soil's pore spaces. Once the surface tension and capillary force between the soil particles is exceeded by that of gravity, the water in the unsaturated zone will flow vertically downward toward the water table.

As infiltration continues with time, the soil moisture increases and the capillary forces begin to decrease (fig. 3-6). This causes the infiltration capacity of the soil to decrease.

Dry soils have high infiltration capacities and soils that have larger amounts of moisture have relatively low infiltration capacities. As long as the intensity and duration of precipitation is such that the infiltration capacity of the soil is not exceeded, infiltration will continue. As soon as the precipitation rate exceeds the infiltration capacity, water will start to collect on and move across the land surface. This is known as runoff. In addition, infiltration decreases with increased slope and/or a decrease in vegetative cover.

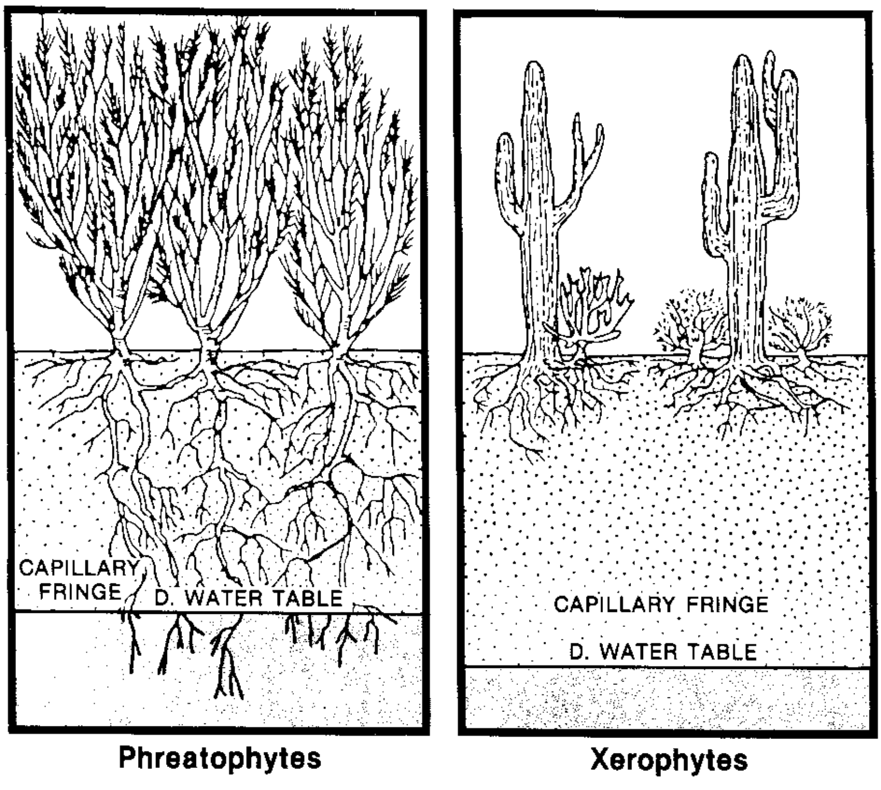


Figure 3-4. *Comparative relationship of phreatophytes and xerophytes to the underlying water table (Source: U.S. geological survey).*

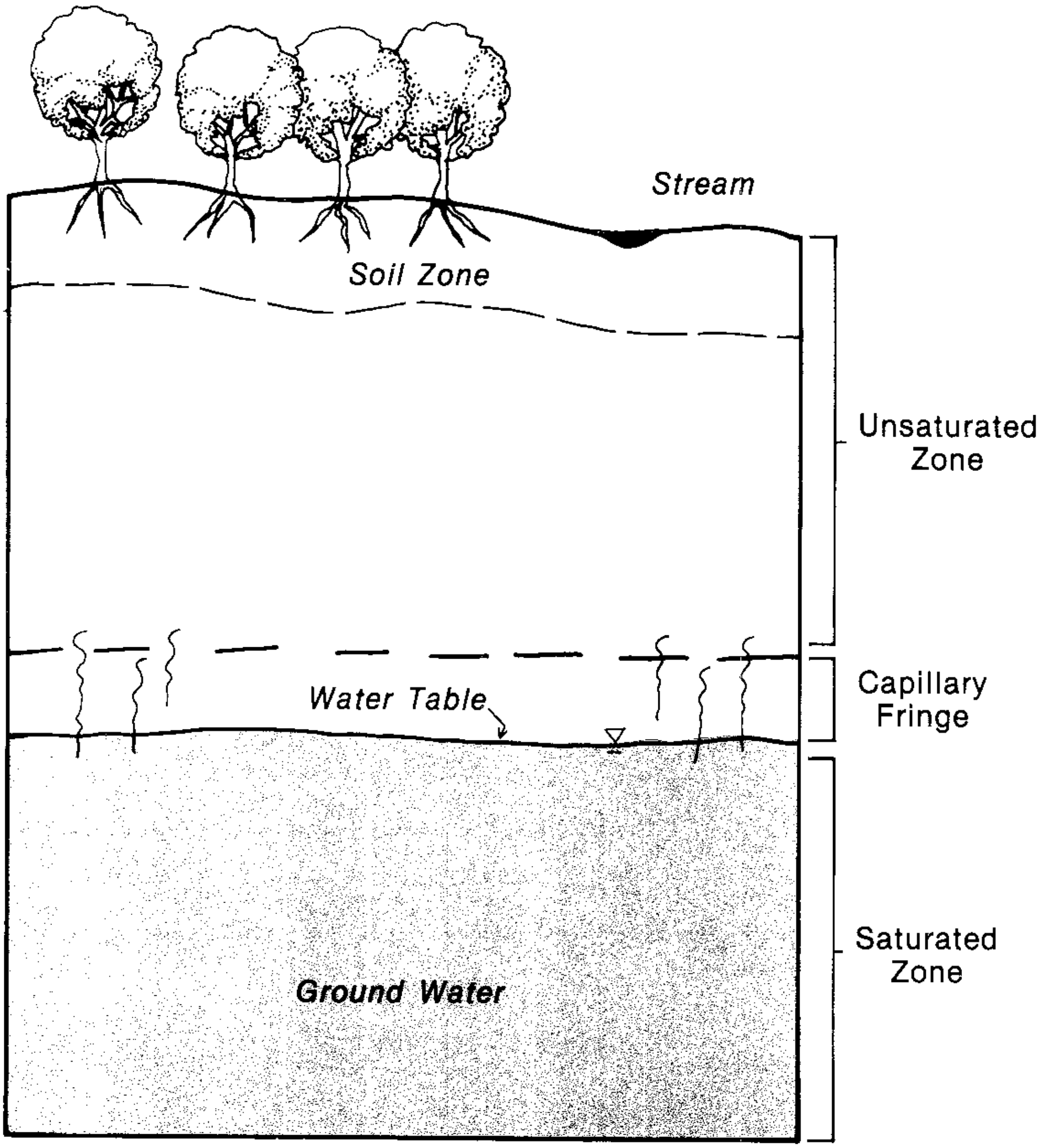


Figure 3-5. *Unsaturated and saturated zones.*

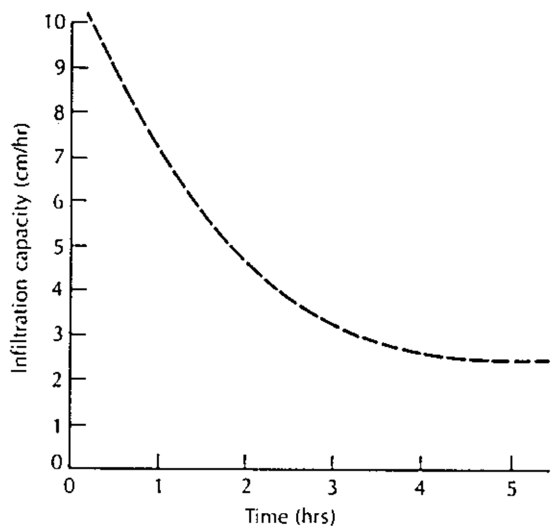


Figure 3-6. ***Infiltration capacity vs time. Decreasing infiltration capacity of an initially dry soil, as the soil-moisture content of the surface layer increases.***

As precipitation ceases and the water drains from the soil, the moisture content will decrease to a point where the force of gravity acting on the water equals the capillary and surface tension forces between the soil particles. Gravity drainage will stop at this point known as the soil's field capacity.

Runoff

Runoff is usually greatest during precipitation events of great intensity and relatively short duration, such as thunderstorms. So much rain falls on the land surface that the soil simply doesn't have the capacity to let it all infiltrate and so it travels along the land surface or stands as puddles. Two factors that greatly affect the rate of runoff are slope and vegetation. Increased slopes and lack of vegetation tend to let runoff water gain velocity as it moves across the land usually resulting in erosion. Vegetation serves to slow down the runoff rate and in many cases may delay this water long enough so that it has the opportunity to infiltrate into the soil.

In arid regions, generally much less vegetative cover is present than in more humid areas. The lack of vegetation, combined with the shorter, more intense rainfall characteristic of arid climates, results in higher runoff potential and subsequent flash flooding.

Surface runoff has two major components: depression storage and overland flow. Runoff water that becomes trapped in puddles is known as depression storage. This water will infiltrate into the soil once the the soil moisture capacity is no longer at a maximum. Water that moves across the land surface as a thin sheet is referred to as overland flow. Eventually runoff water will enter a surface drainage channel where it becomes part of the streamflow.

Base Flow

Although the saturated zone is gaining water from an area where recharge is occurring, it may be losing ground water in an area of discharge where water flows out of the ground. Lakes, rivers, streams, creeks, springs, seeps and bogs usually act as ground water discharge areas. When ground water is discharged into a surface water drainage system, it is known as base flow.

In humid regions, depending upon the time of the year, water tables beneath the land surrounding a stream are often higher than the water level in the stream. This situation results in a ground water base flow contribution to the stream. In arid regions, often there is no baseflow component in the streamflow. This is due to the water table in such areas being usually deep below the land surface and stream level. This situation results in the stream actually supplying water to the ground water zone.

Stream Flow

The amount of water traveling along a particular surface drainage route is known as streamflow. Streamflow has two major components: runoff, which is the surface contribution to streamflow, and base flow, which is the ground water contribution to streamflow. The hydrograph is the basic graphical method used to show the discharge of a stream or river at a certain location with time. The graph is made by plotting stream discharge against time. Figure 3-7 is a typical hydrograph for the Little Kuma River measured at a point just below Jefferson City, during and after a storm event. Notice the relative portions of the discharge that are attributed to baseflow and runoff.

Storage

Recharge occurs when water enters the saturated zone either directly from the unsaturated zone or indirectly from a surface body of water. Beneath the land surface, the water table is in a constant state of flux. During periods of increased precipitation and infiltration, the elevation of the water table rises as more water enters the expanding saturated zone. Likewise, the water table drops during drought periods as less water reaches the water table. During a given period there will be a net amount of ground water present in the system. This amount is known as storage.

A relationship exists between storage and streamflow. When the water table is higher than the adjacent stream level, ground water movement in most cases will be toward and into the stream. This is usually the case in humid regions. Under these circumstances the baseflow portion of the streamflow increases as one moves further downstream. This type of stream is called a gaining or effluent stream. When the reverse happens and water from the stream infiltrates through the stream bed to a lower water table, the stream is termed losing or influent. In this case less water will be in

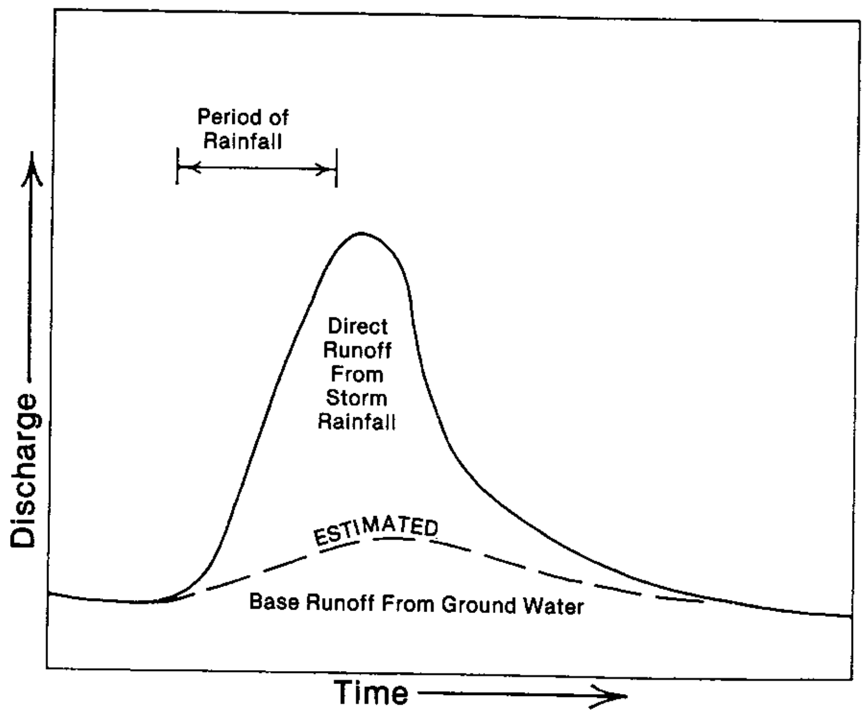


Figure 3-7. ***Storm hydrograph for Little Kuma River, Jefferson City.***

the channel as one moves downstream. This condition tends to be more prevalent in arid regions. Depending upon the circumstances, a stream may change from being a losing stream to a gaining one in just a few hours (fig. 3-8).

Construction and Use of the Hydrologic Equation

The inflow and outflow relationships of the various elements of the hydrologic cycle can be expressed in a simple hydrologic or water budget equation:

$$P = I + E + RO + dGW$$

where:

P = Precipitation

I = Infiltration

E = Evapotranspiration

RO = Runoff

dGW = Change in Ground Water Storage

This is the equation for the simplest of systems. Depending on the specific region and the amount of accuracy desired, a number of other factors may be considered on the right side of the equation. Among these may be soil moisture, interflow, and outflow; of special interest is the discharge or amount of water being pumped from a ground water system.

By calculating the amounts of each element, either through field measurements or by making some logical assumptions, hydrogeologists can use water budget equations to make a number of different types of ground water resource estimates upon which to base ground water management decisions. By quantifying each element of the system, you can see where one or more elements of the system can be varied or changed to bring about a desired response in another part of the system.

For instance, let's say you live in a city that's in an arid climate. This city has a major ground water supply problem in that there is a slow decline in the water table taking place. You want to minimize this decline. It can be done through several approaches. Initially you may decide to reduce ground water production. That would help slow the decline and may even cause a rise. You could also attempt to alter some land use patterns to increase the amount of infiltration taking place. This could be done by using porous pavement in parking lots and in road construction. Perhaps the zoning regulations could be revised to reduce lot coverage and to increase infiltration and recharge potential. Other methods to decrease evapotranspiration or decrease surface runoff could also be used. The hydrologic equation is a basic tool that can be used to determine how a change in one element will affect another.

* * * * *

The Jefferson City Water Budget

Three weeks have passed since the well incident at the Johnson household in Jefferson City. Those first few days afterwards, the phone hadn't stopped ringing at the SCS field office. A few searing newspaper articles had really stirred up quite a few folks—everyone was now worried about what might be in the water they were drinking. Mike Kenton couldn't understand why everyone seemed to call the SCS office—it wasn't supposed to be the local ground water bureau. His agency seemed to be the closest thing to it in Jefferson City. Unlike the USGS, EPA or State Department of Natural Resources, none of which had an office anywhere nearby, the SCS district office was right there and accessible. For now SCS'ers would have to do their best answering the calls.

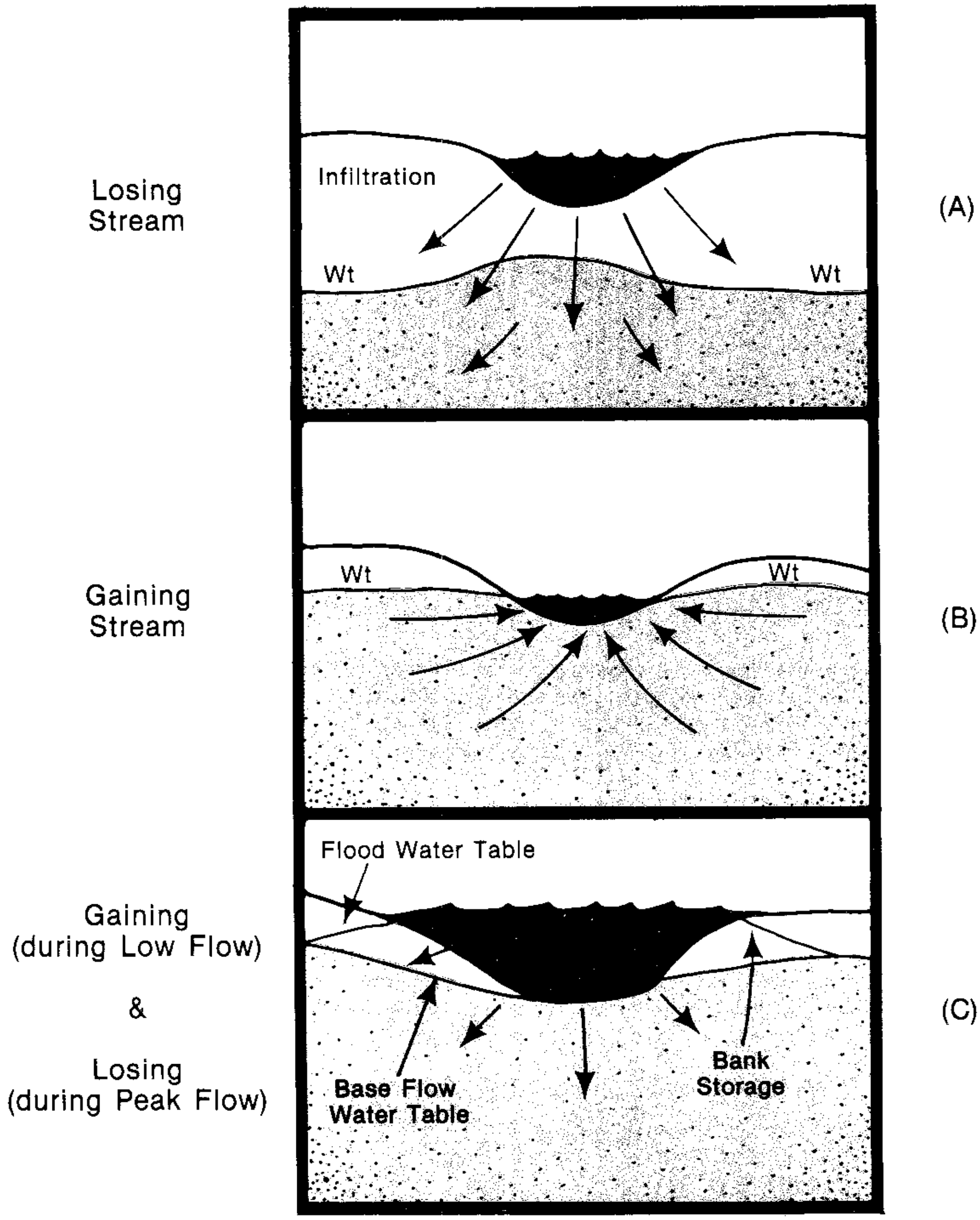


Figure 3-8. *Gaining and losing streams.*

Yes, Skyler Reed had really created a panic. He had dug up his old geology 101 notes and proclaimed himself the local ground water guru. He backed up his articles with quotes from a professor he had interviewed on the phone who taught at a university five states away. This professor had spent the past 18 summers of his life consulting for an oil company and studying the theoretical distribution of some kind of prehistoric bug that lived 175 million years ago in a land far, far away. This bug seems to have inhabited swamps that would one day end up as some of today's prime oil bearing deposits. Kenton wasn't quite sure whether or not a knowledge of oil transferred over easily to the field of ground water, but he had his doubts. Anyway, Reed had made some hasty accusations about possible sources for ground water contamination in Jefferson City. Suddenly every local industry and business was defending itself.

Kenton figured it was time to educate himself a bit on the subject and get some help. He started by calling Ed Stearns, the state geologist. One of his staff people is Janet Jenks, a Soil Conservationist now working at the state office. Kenton had gone through his initial SCS training with her 9 years ago. She worked in a much more urban setting, about 30 miles south of Jefferson City, and he knew that she had dealt with this kind of problem. He hoped that maybe she could put him on to some sources of information. She said she could and invited him down to pick up some material.

The next day he drove down and came away with some names of knowledgeable people, two of which were professors of hydrogeology at the nearby university, and two books, a huge one entitled *Ground Water and Wells* that was supposed to be a pretty complete treatment of the subject and another called *The Climatic Water Budget in Environmental Analysis* by Mather. On that same afternoon he spent an hour or so in the stacks at the university library where he found some USGS water supply papers concerning the region and a couple of hydrogeology text books: *Groundwater* by Freeze and Cherry and *Applied Hydrogeology* by Fetter. He thumbed through them and although they looked pretty technical, he decided that they were worth looking through on the weekend. If nothing else they may help cure the insomnia he'd had for the past few weeks!

Well, the first book Kenton started reading was the book about water budgets. The other books all started out with chapters on the hydrologic cycle so it seemed like a good place to start. The following week he started to collect as much information as he could about the various parts of the hydrologic cycle in the area. He was really surprised when he realized that he didn't have to generate any of the data himself. Most of it had already been collected by other agencies and was available on computer readouts, reports, etc. After a couple of afternoons of work he was able to come up with a fairly comprehensive Jefferson City water budget. Sure, it wasn't perfect and he had to make some broad assumptions to account for gaps in his data, but then that's something that all scientists do. The important thing was that it shed some light on the amount of ground water in the area.

According to Kenton's calculations, the Jefferson City region receives approximately 39 inches of precipitation per year. Of that amount approximately 26 inches is lost back to the atmosphere through evapotranspiration. This leaves about 13 inches of water that may infiltrate into the soil or run off the land surface.

Field measurements of infiltration capacity done by the USGS in the Jefferson City region show that approximately 6 inches of water enters the soil zone each year. Runoff studies indicated that approximately 5 inches of the falling precipitation runs off the land surface.

Figure 3-9 shows Jefferson City's precipitation plotted with evapotranspiration and runoff over one year. It shows several interesting things. First, it indicates that during July-August, precipitation hits some annual lows, while evapotranspiration is at a high. This means that there is a water deficit during which time the soil moisture supply is being exhausted and recharge to the aquifer is probably also at a minimum. Notice that runoff is low during this time also. During the late winter and spring there is a reverse condition: precipitation is high and evapotranspiration is low. During this period there is a water surplus. This kind of information is useful when adjusting seasonal ground water production schedules, conservation measures, and related data.

By plugging this information into the hydrologic equation presented below, Kenton was able to determine that recharge to the Little Kuma River buried valley aquifer was in the amount of 2 inches per year.

$$dGW = P - I - E - RO$$

$$dGW = 39 - 6 - 26 - 5 = 2$$

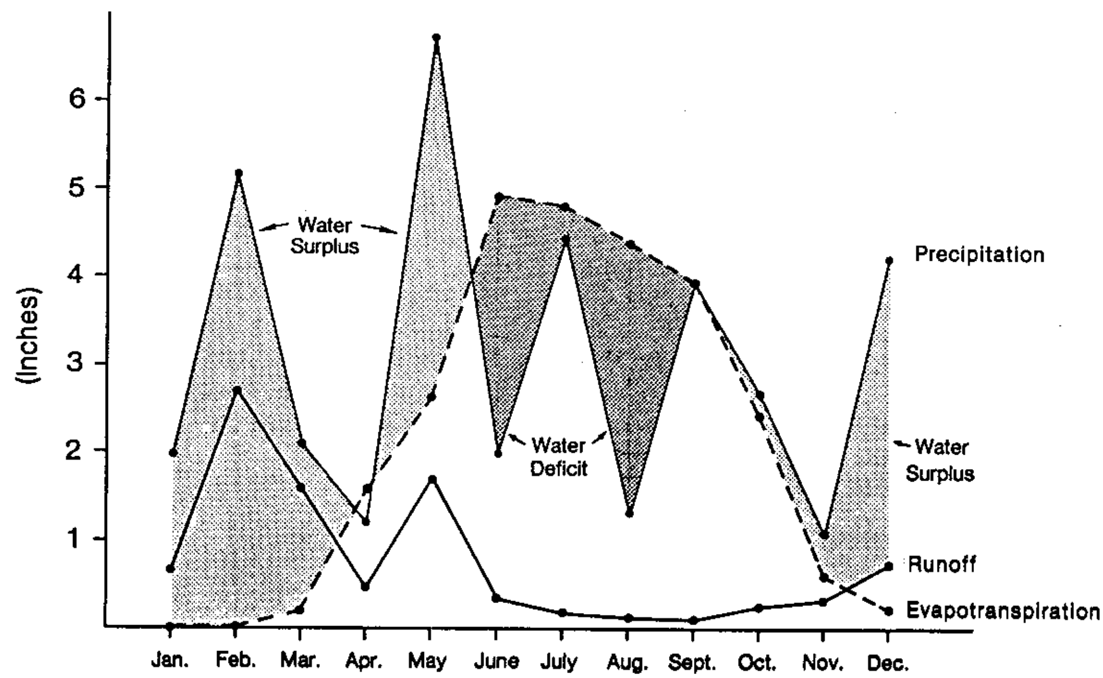


Figure 3-9. *Precipitation, evapotranspiration, and runoff in Jefferson City.*

Only a portion of the recharge that goes into storage, however, can be pumped to the surface. This is because in some years drought conditions will prevail and there will be less water in storage. Also, because of the specific aquifer characteristics and the efficiency of wells, only a fraction of this water will be captured and drawn from the formation. A drought ratio and capture ratio are often applied to express these considerations. In this case, the data provided by the USGS publications indicated that available ground water would probably be an inch or so per year, which is still much more than the ground water demand in Jefferson City.

A graphic representation of Kenton's water budget for the Jefferson City area is presented in figure 3-10.

Kenton, finally understanding the general quantities of water entering and leaving the system, now had other questions such as, what determines how ground water moves through the Jefferson City aquifer and what governs its paths?

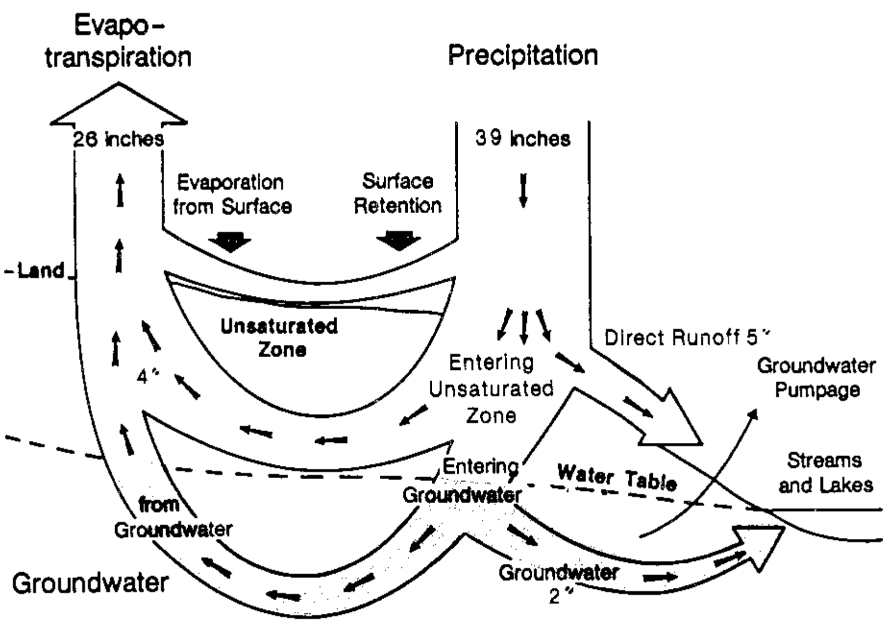


Figure 3-10. *Jefferson City water budget.*

IV. Principles of Ground Water Flow

Hydrologic Properties of Soil and Rock

Water Storage Capability

Earlier we defined an aquifer as a volume of material with capacity to store and transmit water. First, let's consider the storage aspect.

Almost all earth materials have the capability of storing water. In unconsolidated sediments and soils, most of the storage space is found between the individual particles in pore spaces. In denser consolidated rock, the available storage space is usually in cracks or fractures. There are, of course, exceptions to this rule and these will be discussed later. For now it's sufficient to view rock and soil as semi-rigid skeletons containing various amounts of open void space.

Porosity. The amount of pore space in a particular type of earth material is highly variable and depends upon several different factors. The percentage of the total volume of material which is void space is called the porosity, and it is the key factor in determining how much water an aquifer can hold.

Now, how do you measure porosity? There are several scientific ways of doing it, but for the sake of understanding it, a simple example will do. Let's say you take a 5 gallon bucket and fill it with marbles that are all the same size. To determine the amount of pore space within this volume of marbles, slowly pour water into the bucket until it starts to come out of the top. How much water did it take? What percentage is that volume of the total bucket volume? If it took 2½ gallons of water, then that is half the volume of the bucket and represents a porosity of 50 percent. This is a pretty high porosity compared to most natural conditions. This degree of porosity, however, may exist in extremely uniform materials such as glacial sands and gravels, wind-blown sands, and beach deposits.

Factors That Control Porosity. Three factors that control the amount of pore space in an aquifer are: sorting, packing, and the shape of the individual soil or rock particles. You must understand that porosity is independent of the size of the particle involved. That is, you could take a room and fill it with bowling balls that were all the same size and you would have the same porosity as if you filled the same room with ping pong balls.

A mixture of different-sized particles in a single space, however, will influence the degree of porosity. This brings us to the next factor which is sorting. Sorting refers to the uniformity of size of the soil or rock particles. Some materials are made up of masses of particles that are uniform in size. Certain sandstones and unconsolidated glacial sands and gravels are good examples of well sorted materials. Glacial till, on the other hand, is a poorly sorted material. It is made up of different sizes of materials mixed together: sand, gravel, clay, silt, boulders and rock flour, the powdery remains of pulverized rock.

Unsorted or poorly sorted materials will always have lower porosities than well sorted materials. In unsorted materials the smaller grains can actually fill in the spaces between the larger materials, thus reducing the porosity. In other words, the greater the range in the particle size, generally the lower the porosity.

The second factor affecting porosity is packing. How the different particles are arranged has a great deal to do with the porosity of a material. Let's say you take that room full of bowling balls and arrange them in a cubic pattern so that the bottom of each bowling ball rests on the top of the one below it. If this is done throughout the room, you would have what is known as cubic packing. The associated porosity would be relatively high, approaching 48 percent.

If you arrange the bowling balls in a slightly different manner so that each bowling ball rests in the crevice of the four bowling balls below it, then you would have what is known as rhombohedral packing. The associated porosity of this kind of arrangement is about 30 percent.

The shape of the individual particles and their degree of rounding will also influence how a material can be packed. Well-rounded grains will pack together in a cubic or rhombohedral manner and angular, less weathered materials such as talus, broken pieces of rock at the base of a steep slope, will fit together more closely, resulting in lower porosities.

Figure 4-1 illustrates the different ways sorting, packing, and shape can affect the porosity of soil or rock.

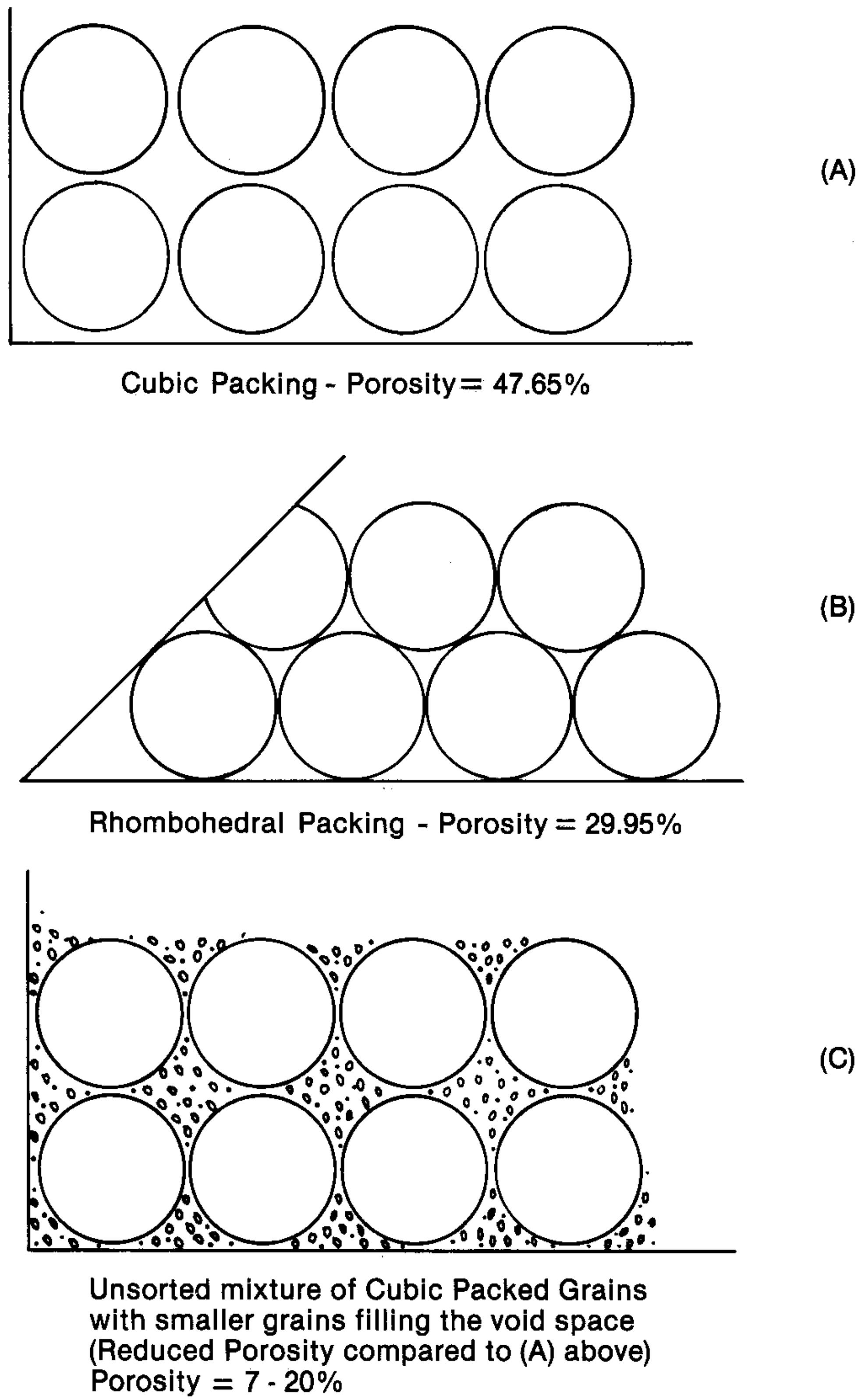


Figure 4-1. ***The effect of packing on porosity.***

Primary and Secondary Porosity. The two different types of porosity are: primary and secondary (fig 4-2). Depending upon the geology in the area one or the other or both types may exist.

Primary porosity represents the pore space that exists between the individual grains making up a mass of rock or soil. It results from the way in which the material was originally deposited or formed. Unconsolidated beach sands, glacial deposits, soils and consolidated sandstones often display this type of porosity. Primary porosity may be reduced with time when minerals carried in solution by flowing ground water precipitate out and form cement that hold the grains together and fill the pores.

Secondary porosity occurs as a result of solutioning and structural changes in a rock unit and can be responsible for the storage and movement of enormous amounts of water. Where there are fractures, joints or bedding planes in an aquifer, ground water can flow freely through these spaces. With time, especially in limestone, rock is actually dissolved along existing crack faces and openings, resulting in even larger flow routes. Subsurface caves, channels and fractures, in reality, act as pipes or conduits for ground water. In areas where such features exist, the determination of the amount of secondary porosity is extremely difficult even for the most experienced geologists. Although these features are most common and well-developed in consolidated rocks, they also occur in unconsolidated deposits as well.

Porosity of Different Earth Materials. Because the particles that make up different earth materials all vary in their individual characteristics, they will, of course, form aquifers with different porosities. As a general rule, because they are unconsolidated, soils have higher porosities than rocks.

Unconsolidated Sediments. The most common types of unconsolidated earth materials are wind blown deposits (loess and dune sand), glacial drift (till, sand and gravel, clay and silts), saprolites or residual soils, alluvium (stream deposited sands, gravels, silts and clays) and lacustrine deposits (lake sediments). There is a wide range of porosity values for these types of materials, depending on how they are packed and sorted. Figure 4-3a lists the hydrologic properties of various unconsolidated sediments and their relative porosity ranges.

Although most clays and clay-rich materials seem quite dense, they may, in fact, have enormous porosities and hold a great amount of water. This is usually because of the size and the shape of the individual clay particles. Often clay particles are rod-shaped or almost book-shaped and have a polarity that tends to make them repel each other when closely packed, thus creating more pore space.

Consolidated Rocks. Now, what about porosity in consolidated materials? We'll start with sedimentary rocks. These rocks may be formed from unconsolidated sediments that are compacted and consolidated by the pressure of the overlying materials. They also may be formed by reactions with fluids in the pore spaces. Consolidation almost always reduces the porosity of the original material. With weathering and time, secondary porosity may occur along joints, fractures, solution channels and bedding planes. This increases the capacity of these rocks to hold water. The reduction of pore space is a result of precipitation of such cementing materials as calcite, dolomite or iron within the pore spaces and of the compaction which rearranges the individual particles.

Porosity in sedimentary rocks can range between 1 to 30 percent. Porosity of certain uniform, clean sandstones can run as high as 30 to 35 percent; some tight dolomites or limestones may have porosities in the range of 0 to 20 percent. Terrains which have well developed subsurface drainage through caves and solution channels are called karst. Remember, in Chapter 1 when you were warned against getting carried away with the underground river idea? Well, in karst areas such features often exist. Porosities can be high—anywhere from 5 to 50 percent. On the other hand, certain sedimentary rocks, such as shale, have porosities in the range of 0 to 10 percent. Figure 4-3b lists the hydrologic properties and porosities of different sedimentary rocks.

Porosity in metamorphic and igneous rocks is also quite variable. These rocks are composed of crystalline minerals formed under high pressure and temperature conditions and have fairly low primary porosities. Secondary porosities in these rocks, however, can make them acceptable ground water sources.

Volcanic igneous rocks such as basalt, which solidify from molten lava on the earth's surface, sometimes have gas bubble voids, joints and fractures that form while the material cools. Pumice, formed from magma that has a high gas content, can have a porosity as high as 90 percent. Settling ash and cinders thrown from a volcano can also create a large amount of pore space in these types of rock.

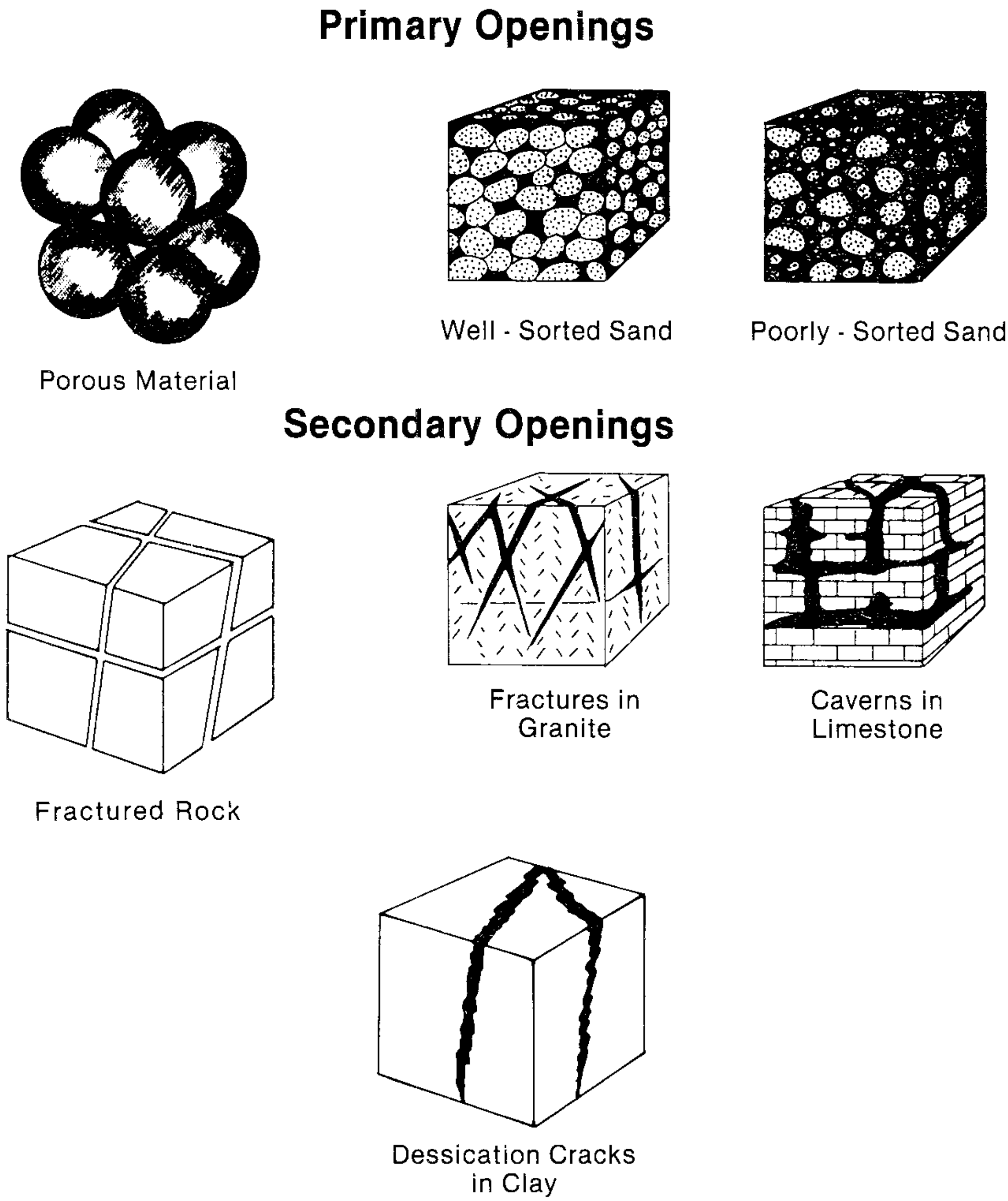


Figure 4-2. *Primary and secondary porosity.*

Deposit	Porosity(%)	Permeability (cm²) (k)	Hydraulic Conductivity (cm/s) (K)
Gravel	25-40	$10^{-6} - 10^{-3}$	$10^{-1} - 10^{2}$
Sand	25-50	$10^{-9} - 10^{-5}$	$10^{-4} - 1$
Silt	35-50	$10^{-12} - 10^{-6}$	$10^{-7} - 10^{-1}$
Clay	40-70	$10^{-15} - 10^{-12}$	$10^{-10} - 10^{-7}$

(A)

Summary of Hydrologic Properties of Unconsolidated Aquifers

Deposit	Porosity(%)	Permeability (cm²) (k)	Hydraulic Conductivity (cm/s) (K)
Sandstone	5-30	$10^{-13} - 5 \times 10^{-9}$	$10^{-8} - 10^{-4}$
Limestone, dolomite	0-20	$5 \times 10^{-13} - 5 \times 10^{-9}$	$6 \times 10^{-8} - 10^{-4}$
Karst limestone	5-50	$10^{-9} - 2 \times 10^{-5}$	$10^{-4} - 1$
Coal	0-1	$10^{-9} - 10^{-11}$	$10^{-6} - 10^{-4}$
Shale	0-10	$10^{-16} - 10^{-13}$	$10^{-11} - 10^{-8}$

(B)

Summary of Hydraulic Properties of Sedimentary Rock Aquifers

Deposit	Porosity (%)	Permeability (cm²) (k)	Hydraulic Conductivity (cm/s) (K)
Unfractured Igneous and Metamorphic Rocks	0-5	$10^{-16} - 3 \times 10^{-13}$	$10^{-11} - 3 \times 10^{-8}$
Fractured Igneous and Metamorphic Rocks	0-10	$8 \times 10^{-12} - 2 \times 10^{-8}$	$8 \times 10^{-7} - 5 \times 10^{-2}$
Fractured Basalt	5-50	$2 \times 10^{-10} - 2 \times 10^{-5}$	$2 \times 10^{-5} - 2$

(C)

Summary of Hydrologic Properties of Igneous and Metamorphic Rock Aquifers

IRIS

Figure 4-3. *Summary of hydrologic properties.*

Porosity in igneous rocks is largely caused by features such as gas bubble voids and tree molds; however, these void spaces are often not interconnected. Therefore, their ability to transmit water is often limited.

Igneous rocks formed deep within the earth tend to have low porosities, between 2 and 5 percent. Of course, with age and weathering, the formation of secondary porosity increases their storage capacities.

Metamorphic rock is formed when sedimentary or igneous rocks are deformed with increased temperature or pressure. Generally the porosity of metamorphic rock is similar to that of igneous rock. Some metamorphic rock, however, was originally sedimentary rock and may possess the original bedding planes and sedimentary features, thereby increasing the potential for secondary porosity. Joints and fractures can also increase the porosity.

Figure 4-3c lists the hydrologic characteristics of unconsolidated, sedimentary and metamorphic rocks.

Water Transmitting Capability

Up until now we have been talking about the water storage capacity of rock and soil as a function of porosity. What makes a good aquifer, however, is not just the ability to store water, but its ability to also transmit water. Good aquifers are unique among our many natural resources in that they actually deliver ground water to points of harvest. Too bad resources like gold, silver and coal don't do the same!

Permeability

The capability of a material to transmit water, or the ease with which water can move through the pore spaces, is known as its permeability. Permeability is a difficult parameter to measure in the field because it varies widely from place to place.

Certain kinds of unconsolidated coarse-grained sediments such as sands and gravels represent some of the best aquifer materials available. These materials tend to have high permeabilities. On the other hand, some unconsolidated sediments such as clay, don't transmit water readily because they have low permeability. This is why clay is often used as a lining for solid waste disposal facilities. Make no mistake, however, clay is not impermeable—water will eventually move through it.

The permeability of a material is a function of the size of its individual pore openings. The smaller the size of the sediment grain, the larger the amount of surface area the water contacts. This increases the resistance to flow of a fluid moving through the space and thus reduces permeability. In fine-grained sediments such as clay, there's a great deal of resistance to flow through the small pore spaces that results in low permeability. Generally, in well sorted sediments, as the grain size increases, so does the permeability. Similarly, as the sorting of a material decreases, the permeability decreases.

The permeability of consolidated rocks depends on the size of the pore spaces and the degree to which they are connected. As we discussed earlier, most of the pore space present in consolidated rocks is caused by secondary porosity. As secondary porosity increases in consolidated rocks, so does permeability. Weathering can increase permeability. As the rock breaks down, the pore spaces tend to become more interconnected, fractures and joints enlarge, and permeability increases.

Now don't get the idea that as porosity increases, permeability always does, too. That is not the case. For example, clay can have a high porosity and at the same time, because of the small grain size, have low permeability. Some shales and clays are able to hold a great amount of water. Getting this water to drain out, however, can be difficult.

Principle of Hydraulic Conductivity

Hydrogeologists use a parameter known as hydraulic conductivity to describe the rate at which water can move through a permeable medium. Each type of earth material has a different hydraulic conductivity, also known as "K". Hydraulic conductivity is measured in the velocity units of length over time and is sometimes referred to as the coefficient of permeability. Often the terms permeability and hydraulic conductivity are used interchangeably.

The most important thing to understand about hydraulic conductivity is that higher values mean that in a given amount of time, larger amounts of water are able to move through the material. Clean sands and gravels usually have high hydraulic conductivities.

Variations in Hydraulic Conductivity

Hydraulic conductivity of a material is governed by the size and shape of the pores, the interconnections between the pores and the physical properties of the fluid flowing through the material. If the interconnecting passageways are small, then the volume of water passing through them is restricted and hydraulic conductivity is quite low. In coarser sediments, such as sand and gravel, the interconnections between the pores are relatively large, resulting in high conductivities.

Hydraulic conductivity also varies with the fluid moving through the aquifer material. It is proportional to the specific weight of the fluid. This means that the hydraulic conductivity of a formation transmitting crude oil will be different than that of the same formation carrying water. The temperature of the fluid also affects the hydraulic conductivity. The viscosity and density of water are both determined by its temperature. Cooler water is naturally more viscous and therefore has more resistance to flowing through a material.

Homogeneity and Heterogeneity

Hydraulic conductivity can be uniform or highly variable within an aquifer. There are four terms that describe the degree of variability: homogeneity, heterogeneity, isotropy, and anisotropy. Homogeneity and heterogeneity deal with variability in magnitude with location, whereas isotropy and anisotropy relate to direction.

Everywhere within a homogeneous aquifer, the hydraulic conductivity is of the same magnitude. An example of a homogeneous aquifer would be a room filled with golf balls, stacked one on top of another, all the same shape and size. In nature similar conditions are sometimes encountered in uniform sandstones and well sorted sands and gravels.

In a heterogeneous aquifer the conductivity varies with respect to position. Take the same room full of golf balls stacked on top of each other and randomly add a few volleyballs. The result would be different arrangements of balls in different areas of the room. The best geologic examples of heterogeneity would be areas such as glacial terrains where there are mixtures of different types of sediments, till, sand, and gravel.

To sum things up, if hydraulic conductivity values are the same in all positions within a geologic formation, the formation is homogeneous. If the hydraulic conductivity varies with position, the formation is heterogeneous.

Isotropy and Anisotropy

Isotropy and anisotropy deal with the direction of hydraulic conductivity within a formation. Isotropy is sometimes thought of as a more localized measure of conductivity within an aquifer. It's where conductivity is equal in all directions. Consider the room filled with golf balls and volleyballs. Although the balls are randomly arranged, there are isolated pockets consisting of all golf balls or all volleyballs. If we speak of each of these individual pockets, we have isotropy. Sometimes uniform sand or gravel lenses or channels are in glacial tills. Within the sand or gravel lens an isotropic condition exists, meaning that the hydraulic conductivity is equal in all directions. Looking at the formation as a whole, it would be considered anisotropic (fig. 4-4).

Most often anisotropic conditions exist in geologic formations. Hydraulic conductivity varies with direction, usually being greater in the horizontal direction than in the vertical direction. An example would be an interbedded sandstone and siltstone formation where water moves horizontally through the sandstone quite easily, but vertical movement from the siltstone to another sandstone layer below may be slow. Another example would be fractured granite where movement is through the fractures, but little or no movement is through the unfractured part. Hydraulic conductivity in the fractures themselves is greater than the surrounding rock and so this is considered an anisotropic condition. The vertical and horizontal conductivities in alluvial or stream deposits are also quite different.

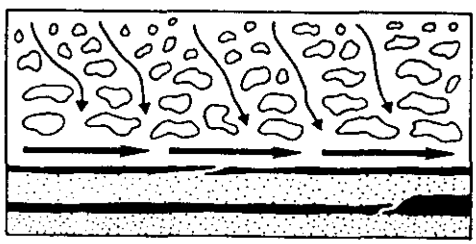


Figure 4-4. *Anisotropy of alluvial deposits: horizontal conductivity greater than vertical conductivity.*

So, if the hydraulic conductivity is independent of the direction of measurement at a certain point in a geologic formation, the formation is isotropic at that point. If the hydraulic conductivity varies with the direction of measurement at a point in the geologic formation, the formation is anisotropic.

Because every material has a directional and magnitudinal component of conductivity, a combination of homogeneity or heterogeneity, isotropy or anisotropy, is possible in every case (fig. 4-5). In a homogeneous, isotropic medium, usually the grain size is uniform throughout. In a homogeneous, anisotropic medium, the grain size is uniform, but the grains may be oriented in a particular direction, as in shale formations. There may be an orientation of direction of the individual grains such as in a clay formation. In a heterogeneous, isotropic medium, the grain size may be uniform within a locality, but different between localities. This type of condition may be encountered in a beach deposit. In a heterogeneous, anisotropic medium, hydraulic conductivity varies in both location and direction. An example is the layering of poorly sorted materials within a glacial outwash deposit or sandstone. These are the only four combinations of these parameters that are possible.

Transmissivity

The expression of hydraulic conductivity throughout an entire thickness of an aquifer is called the transmissivity. It is calculated by multiplying the hydraulic conductivity of the materials by the saturated thickness of the aquifer. Transmissivity is defined as the rate of flow in gallons per minute through a vertical section 1 foot wide and extending the full saturated height of an aquifer under a hydraulic gradient of one. Transmissivity is usually symbolized by the capital letter ''T'' and is expressed numerically in units of length squared over time.

Aquifer parameters such as hydraulic conductivity and transmissivity are usually determined by three methods: pump tests, analysis of the hydraulic properties of aquifer materials, and laboratory calculations.

In present day groundwater studies, great reliance is placed on the results of field tests from which the hydraulic conductivity and transmissivity of an aquifer are computed. Determination of these parameters enables hydrogeologists and engineers to make estimates of how much water certain aquifers will be able to yield and at what rate. More about pump tests later.

Aquitards and Perched Water Tables

Sometimes, a localized lens or layer may be in a formation. If it is relatively impermeable, it may hinder the free movement of water. This is called an aquitard. Clays and tills within glacial aquifers are usually considered aquitards because they greatly inhibit the vertical movement of water and yield little water. This is not because they have low porosities, but because they have low permeabilities. If a layer or zone is unable to yield any water at all, it is termed an aquiclude. Most materials, however, are able to yield a small amount of water.

When a lens of low permeability material exists within a more permeable formation, water that is moving downward will be intercepted by this layer and accumulate on top of it. This creates a layer of saturated soil above the main water table. The phenomenon is called a perched aquifer or perched water table (fig. 4-6). There is a finite amount of water that a perched aquifer can hold before water starts to seep off the trailing edges downward toward the main water table. Perched water tables are often encountered in glacial outwash aquifers and in volcanic areas where low permeability zones of ash are between high permeability basaltic layers. Most often these perched water tables are only capable of yielding water for low levels of consumption.

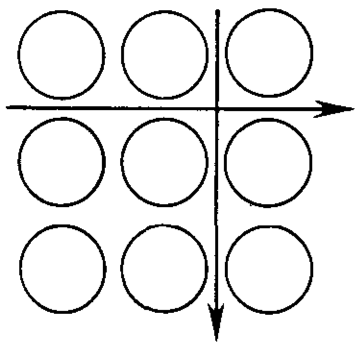
Springs

Springs are of several different types (fig 4-8a). Probably the most common are contact springs. Contact springs usually are where a mass of permeable rock or unconsolidated material overlies another mass of impermeable material. Water moves downward through the more permeable material and is deflected horizontally along the surface of the less permeable material until it reaches an outcrop where it flows out on the land surface. Often the contact between two rock units which are not outcropping at the surface is indicated by this type of spring on a valley wall.

In the Jefferson City case study area, along the river valley wall, there are many contact springs indicating the contact between the unconsolidated glacial deposits and the buried shale bedrock.

Homogeneous, Isotropic Medium

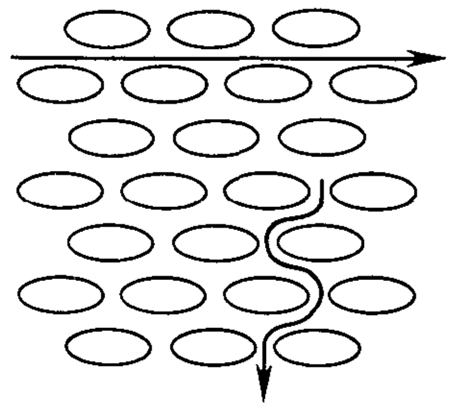
Hydraulic Conductivity; $K_x = K_y$
(Grain size is uniform)



ex. well sorted sand

Homogeneous, Anisotropic Medium

Hydraulic Conductivity; $K_x \neq K_y$
(Grain size is uniform)

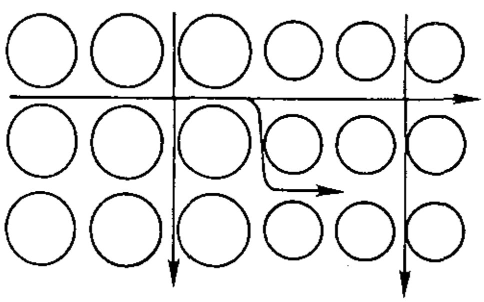


ex. clay layer

Combinations of Homogeneity With Isotropy and Anisotropy

Heterogeneous, Isotropic Medium

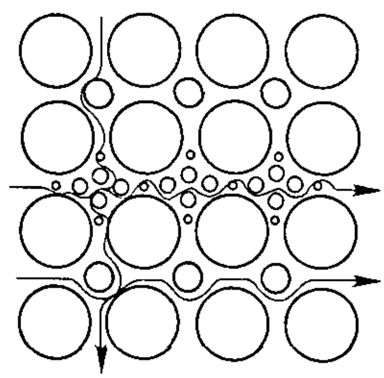
(Grain size is uniform at each locality but is different between localities; the same is true for K)



ex. lateral grain size change

Heterogeneous, Anisotropic Medium

(Both grain size and hydraulic conductivity (K) vary spatially)



ex. layering of sorted material and poorly sorted material; sandstone, glacial till, sandstone

Combination of Heterogeneity with Isotropy and Anisotropy

Figure 4-5. *Variations in hydraulic conductivity.*

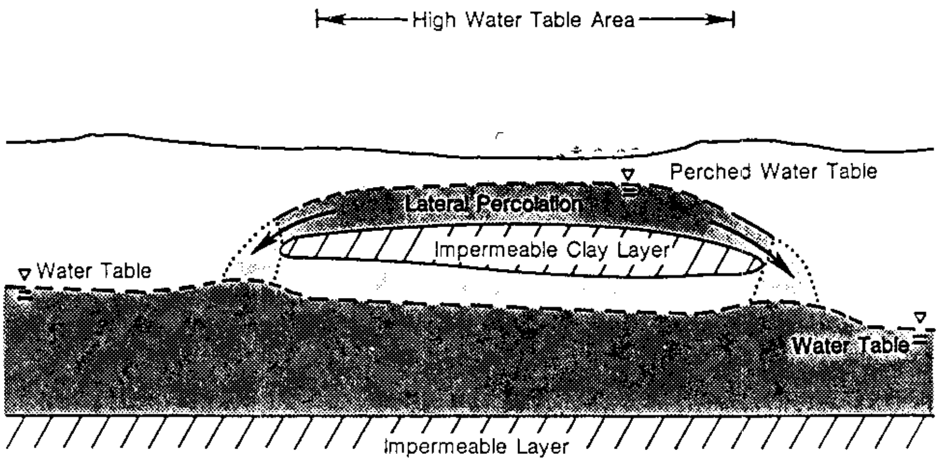
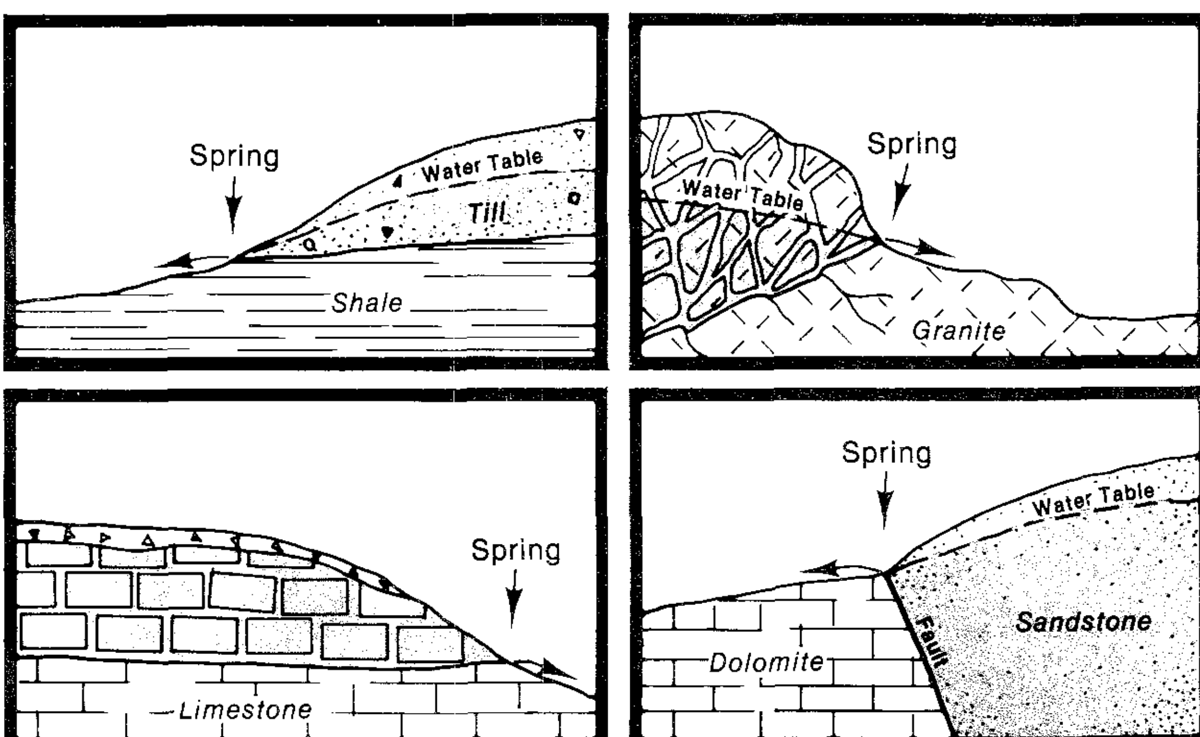


Figure 4-6. ***Drainage problem caused by a perched water table.***

Spring	Occurrence	Type of Opening		Water Quality	Features Produced
Depression	Low-lying outcrops below the upper limit of the water table	Irregular void spaces between rock particles	1 -10 gpm depending on gradient permeability	fair-excellent	None in valleys; slumps and swamps in humid regions
Contact	Impermeable material out-crops below permeable material	Sand and gravels: irregular voids Bedrock: joints, fractures Limestone: tubular	1 - 10^3 gpm	fair-excellent	Travertine ($CaCO_3$)
Fracture, Joint, and Tubular	Land surface outcrops below water table	Fractures, bedding planes, tubular	1 - 10^2 gpm	good-excellent	Travertine ($CaCO_3$)

(A)

Characteristics of Springs



(B)

Common Types of Springs

Figure 4-7. *Characteristics of springs.*

Often low spots in the topography result in depression springs. These are located where the topography actually dips below the main water table forming marshes or small ponds. These types of springs are often seasonal in nature.

Another type of spring is called a fault spring, which may originate where rocks are faulted. When faulting occurs, permeable zones may be brought into contact with impermeable zones along the fault line. When water moving through the permeable zone reaches an impermeable zone, it is forced downward or up to the surface along the fault contact. Figure 4-7 shows examples of faults enhancing and inhibiting ground water flow.

Joint or fracture springs also are in consolidated rocks. When there are elaborate joint patterns, sometimes water can intersect the land surface.

Some of the largest springs are in karst areas where there is extensive development of secondary solution porosity indicated by solution openings, sinkholes, and caverns. Springs are often formed where these features intersect the land surface.

Some springs flow all year long, and others flow only during wet periods. Spring water may come from near surface sources or from great depths. The difference in sources results in great variations of chemical constituents and temperature.

Confined and Unconfined Aquifers

Ground water can exist within aquifers under two very different physical conditions. When the water table is exposed to the atmosphere through a series of interconnected openings in the overlying permeable material, the aquifer is said to be an unconfined or a water table aquifer. This is perhaps the most common type of aquifer.

In a confined aquifer, the water table is separated from the atmosphere by an impermeable layer of material. Ground water in these aquifers is under pressure. Recharge to this type of aquifer generally occurs in a recharge area where the aquifer is exposed at the surface or through slow leakage from the overlying confining layer.

Often when wells are drilled into confined aquifers, water flows up under pressure through the opening and out onto the land surface; sometimes it rises above the land surface. The level to which the water rises in the opening or casing is called the potentiometric surface. It is analogous to the water table in an unconfined aquifer. If the potentiometric surface is above the land surface, a flowing well occurs. Confining pressure often results when the water table in the recharge area is higher than the point at which the well intersects the confined aquifer material.

Flowing conditions can be good or bad depending upon the circumstances. In areas where water is scarce and deep, such conditions can transmit great amounts of water to the surface without the need of pumps. Flowing conditions can be quite troublesome in some drilling operations if not anticipated ahead of time.

In some cases, the water table in an upper, unconfined aquifer can drop below the bottom of a well because of downward leakage through a confining aquitard into a lower confined aquifer where water is being withdrawn. Pumping from confined aquifers can often cause a decline in the potentiometric surface which can induce a certain amount of leakage from the aquifer above the confined material. When this occurs the aquifer often has leaky conditions. Any time that there is a marked difference in head between neighboring aquifers, there is potential for leakage between them. This is because even the most impermeable natural materials have some ability to transmit water. Frequently secondary features such as fractures or faults will permit greater leakage than might be predicted based upon the characteristics of the confining materials.

Unconfined and confined aquifers (fig. 4-9) also have different water storage and yield characteristics (fig. 4-10). Given two aquifers of the same volume and composed of the same materials, one unconfined and one confined, the unconfined aquifer will yield more water per unit decline in head. The confined aquifer releases water from storage mainly as a result of compression of the aquifer and the expansion of the water upon pumping. Confined aquifers are not actually dewatered upon initial pumping. The amount of water released from storage in an aquifer of constant thickness per unit area per unit decline in the head (we'll talk about hydraulic head in just a minute) is called the storage coefficient (S).

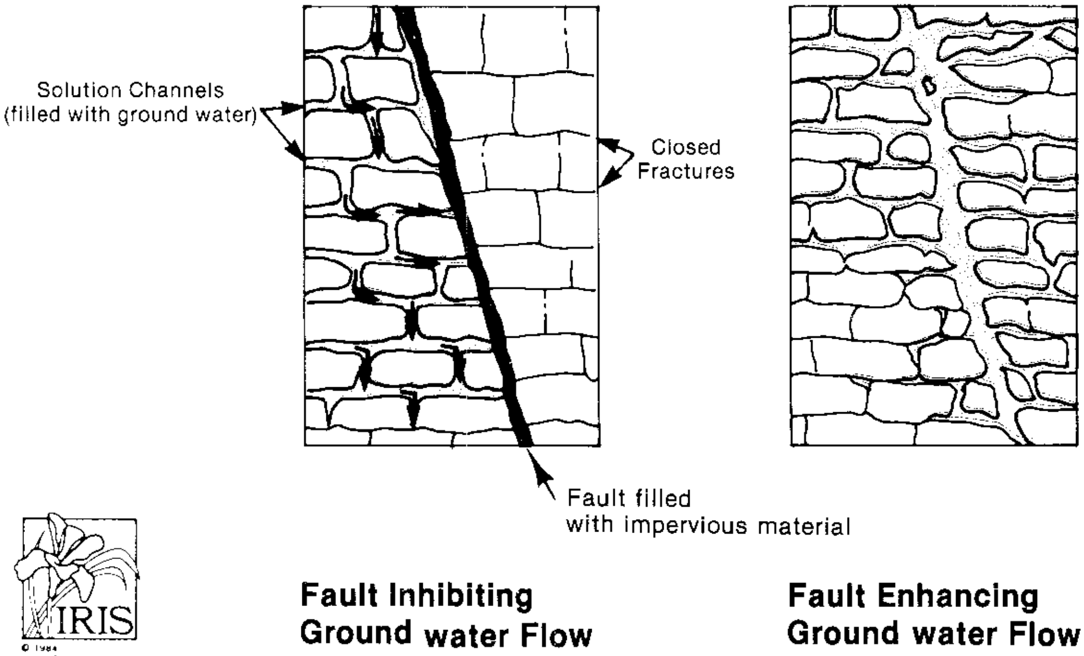


Figure 4-8. *The effect of a fault on ground water flow.*

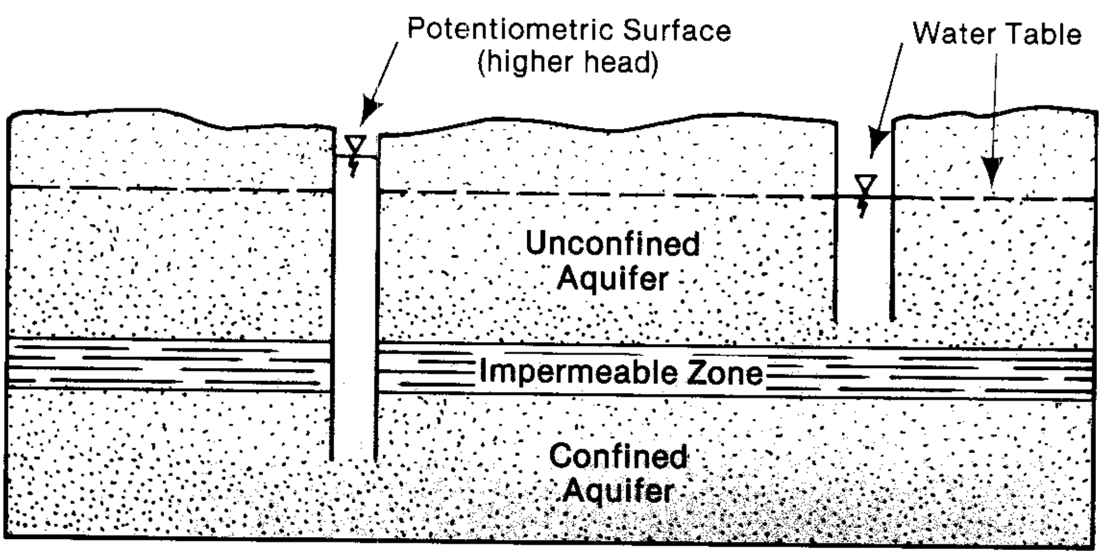


Figure 4-9. *Unconfined and confined aquifers.*

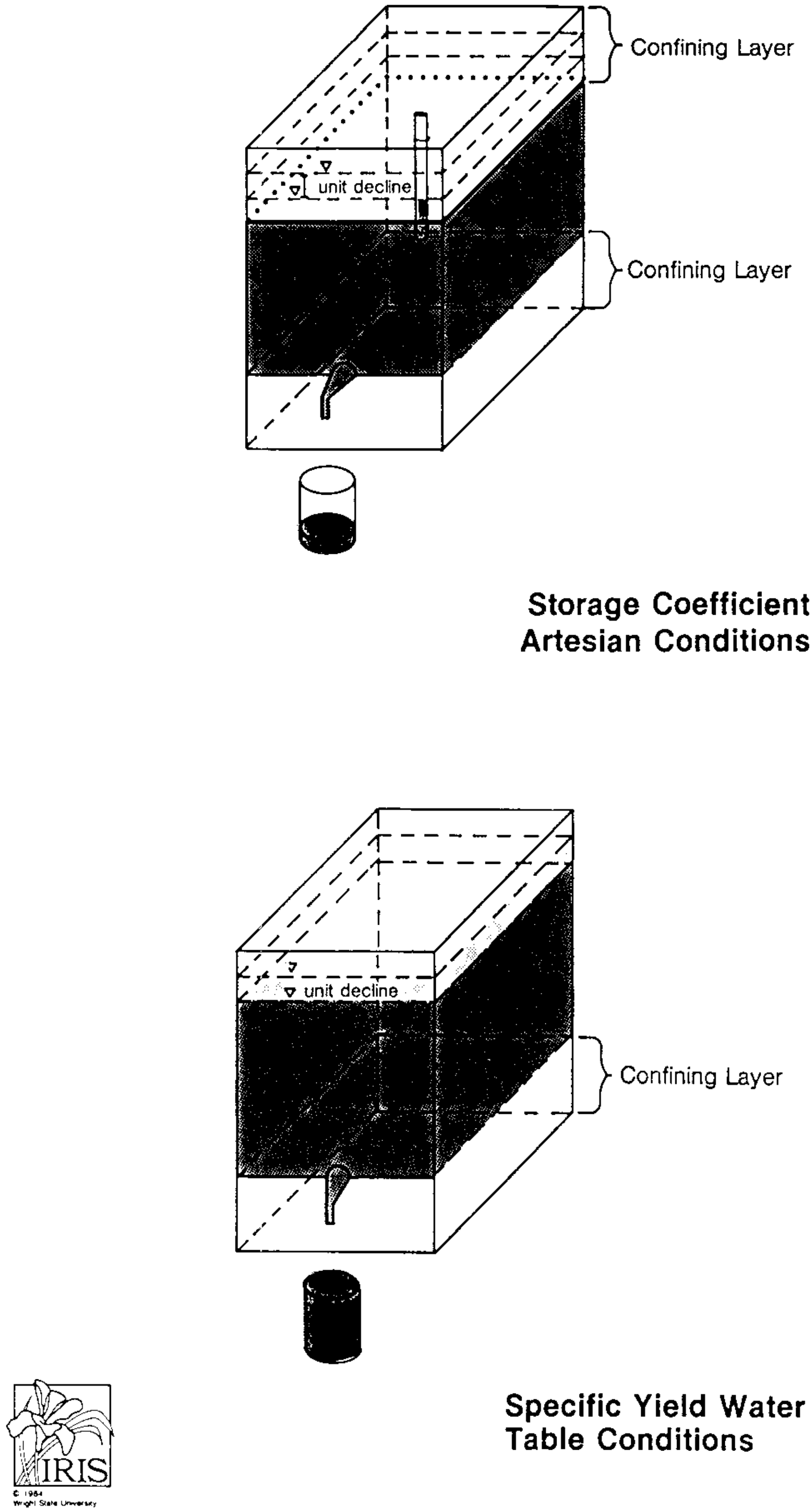


Figure 4-10. *Aquifer storage parameters.*

In an unconfined aquifer, pumping causes gravity drainage and dewatering of the formation. This amount is known as the specific yield (Sy) and is defined as the volume of water drained from storage under gravity per unit area per unit decline in head. Specific yield in an unconfined aquifer is analogous to the storage coefficient in a confined aquifer.

*   *   *   *   *   *

Principle of Hydraulic Head

Once in a while a boost of motivation may come out of nowhere. It may come in the form of a little recognition from someone you never thought appreciated your work or a sunny, spring morning when you made yourself a terrific western omelet. Mike Kenton's motivation came in the form of a phone call.

It was an ordinary day in late July, Kenton was spending the morning at the district office catching up on some paper work. In the past couple of weeks, some of the uproar over ground water contamination had died down. At least it hadn't been on the front page lately. Maybe things were getting back to normal. And then the phone rang. . . .

Kenton picked up the receiver and the voice on the other end introduced himself as Colonel Randolph Banks and added that he was retired from the United States Marine Corps. From the tone of the man's voice he hadn't been retired long—it made Kenton straighten up in his chair in anticipation of a command. Kenton had heard a similar voice before, perhaps his father's or his army drill sergeant's; he wasn't sure, but it was the kind of voice that made you see value in listening before you even knew what was to be said. The Colonel continued.

"Are you the young man who knows all about the soil and water around here?"

"Yes, sir," Kenton replied, adding "sir" not because it was something he normally did, but because it just seemed appropriate and safe. He might have saluted if it weren't for the phone receiver in his hand.

"Well, what can you tell me about it?" the Colonel snapped.

"Ah well, wwwhat do you want to know, sir?" There was a long pause that made Kenton get ready to look for a bunker and then . . .

"How old are you, young man?"

"Thirty-four, sir."

"Ever been in the military?"

"Yes, sir," he eagerly volunteered to the Colonel, thinking it would put them on some common ground. "The Army, sir," Kenton stated proudly. There was another long pause in which Kenton could almost taste the disapproval.

"Well, you *still* might be able to help me," said the Colonel adding another question. "Know anything about engineering?"

Kenton changed the receiver to his other hand, which wasn't sweating. "A little, sir."

"Well, young man, a little may be enough." With that the Colonel went on to explain that he had just retired from the Marines and was planning to buy some property outside Jefferson City to build a house. It seemed that he had grown up in Jefferson City and was "coming home to settle down." Before he did, however, he wanted to know more about the ground water problems he'd been hearing about on that side of town, which happened to be out where the Johnson's lived, in Kuma Estates. He said it didn't matter what was in the water as long as he could drill a well that was upgradient from the source. Kenton explained to him that they didn't know yet where the source was or even the kind of contaminant. Another long pause.

"Well, do you know anything about the hydraulic gradient out that way?" the Colonel asked with the first sign of weakness in his voice. It just happened that "hydraulic gradient" was not one of the terms in Kenton's limited engineering vocabulary. Maybe it would be in the next chapter in the hydrogeology book he'd been reading.

"Excuse me, sir?", Kenton asked hoping for another hint.

"Which way does the ground water flow?" asked the Colonel.

"I'm not sure, sir," Kenton replied, slumping down in his chair.

"Well, can you have that information for me late next week?" the Colonel asked.

Kenton thought for a split second about whether it was a question or a command and said, "Yes sir," realizing that he had just blown any hope of a reasonably relaxed week and weekend.

"Talk to you next week," the Colonel said, deserting the other end of the line.

A little voice in Kenton's head said "at ease" as he put the receiver down and wiped his brow.

He sat back and thought about what he'd just gotten himself into and about the seriousness in the Colonel's voice. Suddenly for the first time in this whole series of events, Kenton realized something he hadn't yet thought about. Up until now he'd been thinking about the contamination problems in terms of the people who already lived here and not what effect it would have on the future growth of Jefferson City. A dose of motivation had hit home. Kenton uncovered one of his hydrogeology books and looked up hydraulic gradient.

* * * * * *

The determination of ground water flow direction in the field is done through the use of piezometers. Simply, a piezometer is an open pipe which has been inserted into the earth and used to measure the total fluid energy of water. A piezometer is open both at the top and the bottom. When water is encountered, it rises within the pipe in direct proportion to the total fluid energy at the bottom of the piezometer.

The total fluid energy or "hydraulic head" is made up of the elevation head and the pressure head. The elevation head corresponds to the elevation of the point of measurement above a datum (usually sea level). The pressure head is the pressure exerted by the column of water between the point of measurement and the level to which the water rises in a well. Both components of head are measured in units of length. The total hydraulic head is reflected in the level to which water will rise in a piezometer. Figure 4-11 shows these relationships.

Let's say you insert a piezometer 220 feet into an unconfined aquifer and get a total hydraulic head measurement of 800 feet above mean sea level (msl), (fig. 4-11). Then you move 500 feet away on the same elevation and insert another piezometer to the same depth. Here, you measure the water table elevation, which is the hydraulic head, at 750 feet msl. The elevation is higher in one piezometer than the other. Between the two piezometers you have a head differential of 50 feet. From this you can determine which way the ground water flows. Ground water always flows from higher to lower total head. If you want to calculate the hydraulic gradient between these two points, just take the head differential and divide it by the distance between the two points. In this case you'd have 50 feet divided by 500 feet or a hydraulic gradient of 0.1.

In unconfined aquifers, water table measurements can be used to determine the direction of ground water flow because the top of the water table actually marks the position of total head. The natural ground water flow will be from areas where the water table is high to areas where the water table is lower.

In confined aquifers ground water flow direction can be determined by measurement of the elevation of the potentiometric surface. Figure 4-12 illustrates that the water table surface does not always mimic topography especially under confining conditions. Although there is usually some subdued reflection of the topography in the surface of the water table in unconfined conditions, don't make the mistake of assuming that the flow of ground water is always downhill topographically (vs. down-gradient). Remember, its flow is governed by the hydraulic head. Even beneath level topography, the water table may slope considerably. This is most likely caused by differences in the hydraulic conductivity of the underlying materials or by proximity to a discharge area. In the same situation, water tables in high conductivity material tend to be deeper than water tables in lower conductivity material. Figure 4-13 illustrates this phenomenon in a transitional zone between limestone and sandstone.

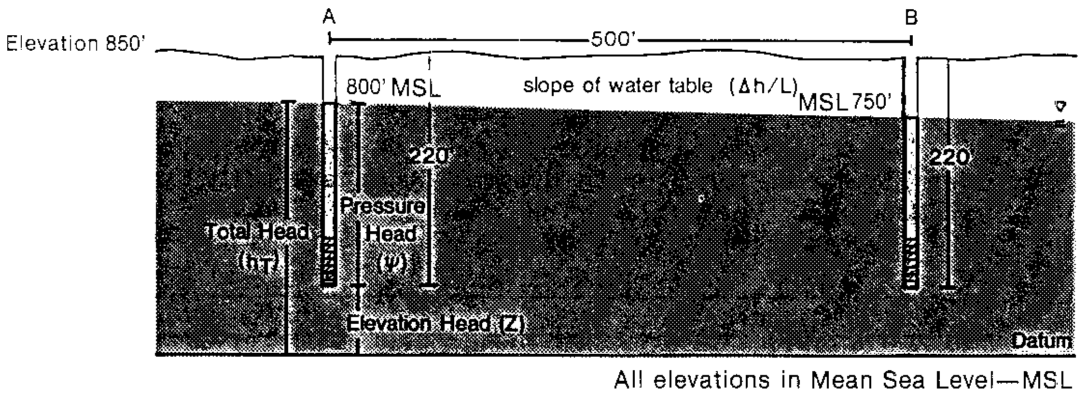


Figure 4-11. ***Relationship of total head to pressure head and elevation head.***

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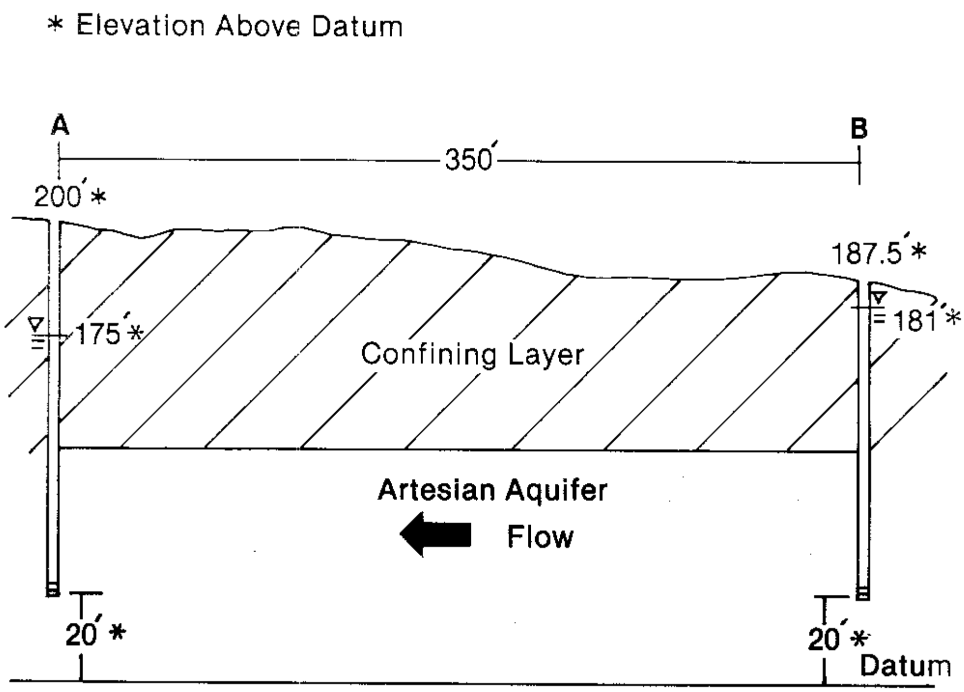


Figure 4-12. *Flow in a confined aquifer.*

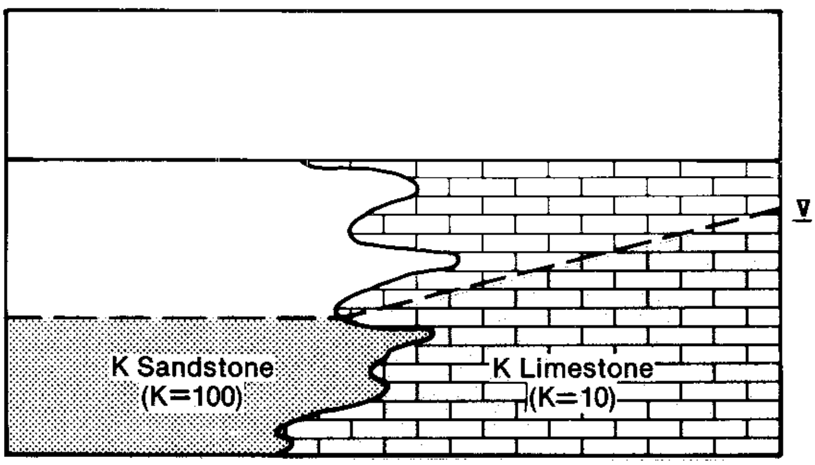


Figure 4-13. ***Relationship between hydraulic conductivity and water table gradient.***

Because of the leakage from one aquifer zone to another, the head may vary vertically more than might be caused by elevation differences. Clusters of piezometers (nests) can also be arranged to determine vertical hydraulic gradients. Figure 4-14 shows such an example.

In addition to determining the direction of groundwater flow, once you establish several points of known head elevation, you can map the surface of the water table in much the same way as a contour map displays topography. It's just a matter of connecting points of equal water table elevation or points of equal hydraulic head. These are known as equipotential lines. On a water table map flow lines can be drawn from points of high hydraulic head to points of low hydraulic head simply by intersecting the equipotential lines at right angles. Schematic representations called flow nets are frequently used to illustrate ground water flow in the vicinity of a well. Examples of these will be presented a bit later.

* * * * * *

After reading up on hydraulic gradient and ground water flow, Kenton set out to map the ground water flow in the area. He started by collecting water table elevations and digging through the well logs on file at the county health department.

He obtained some water table measurements from the city's municipal well field where they recorded that information daily and from a couple of non-community water suppliers serving mobile home parks, campgrounds, etc. The USEPA and the USGS also had some monitoring well information which was useful.

From the data he picked a number of wells that had water table elevations taken about the same time or at least in the same year and season. After plotting those water table elevations on a topographic map, he then drew contours through similar elevations producing a contour map of the surface of the water table. By plotting water table elevations, he was assuming that the aquifer was unconfined. He then plotted the direction of ground water flow by drawing flow lines from points of higher to lower water table elevation, taking care to intersect the equipotential lines (lines of equal hydraulic head or water table elevation) perpendicular to the flow lines. Figure 4-15 shows a simplified version of his water table/ground water flow map.

* * * * * *

Local and Regional Ground Water Flow

Ground water flow can be locally or regionally extensive. The path of ground water flow can be on a small shallow scale only including a single aquifer or basin. When impermeable material encloses a basin, the prevailing ground water flow may be just from recharge to discharge zones within that basin. Under most circumstances, the higher elevations will be recharge areas and will be characterized by deeper water tables. Discharge areas will be in the low lying areas and will usually have shallower water tables. In general the water table will subtly mimic the topography, sometimes actually intersecting the land surface at the bottoms of the valleys.

The ground water flow may be on a much more extensive scale between basins. Figure 4-16 shows an example of local and regional flow as it is in the Great Basin Region.

Ground Water Flow to Wells

What happens in an aquifer when ground water is pumped from a well? The answer depends upon several factors: the type of aquifer material and its hydraulic characteristics, the type of conditions that prevail (unconfined and confined boundaries, homogeneous, isotropic), and the rate of pumping.

Cones of Depression and Zones of Influence

Let's first assume that an aquifer is composed of material that is homogeneous and isotropic and that unconfined conditions exist. The onset of pumping creates a head differential between the bottom of the well and the surrounding aquifer. The water will move toward the well where the hydraulic head is lower. As water enters the well and is withdrawn, there is an initial drop in the water table in the vicinity of the well. This is known as drawdown and results in a cone of depression around the well. The area of an aquifer that is affected by a pumping well or the area in which groundwater is actually flowing towards the well is called the zone of influence. The shape of the cone of

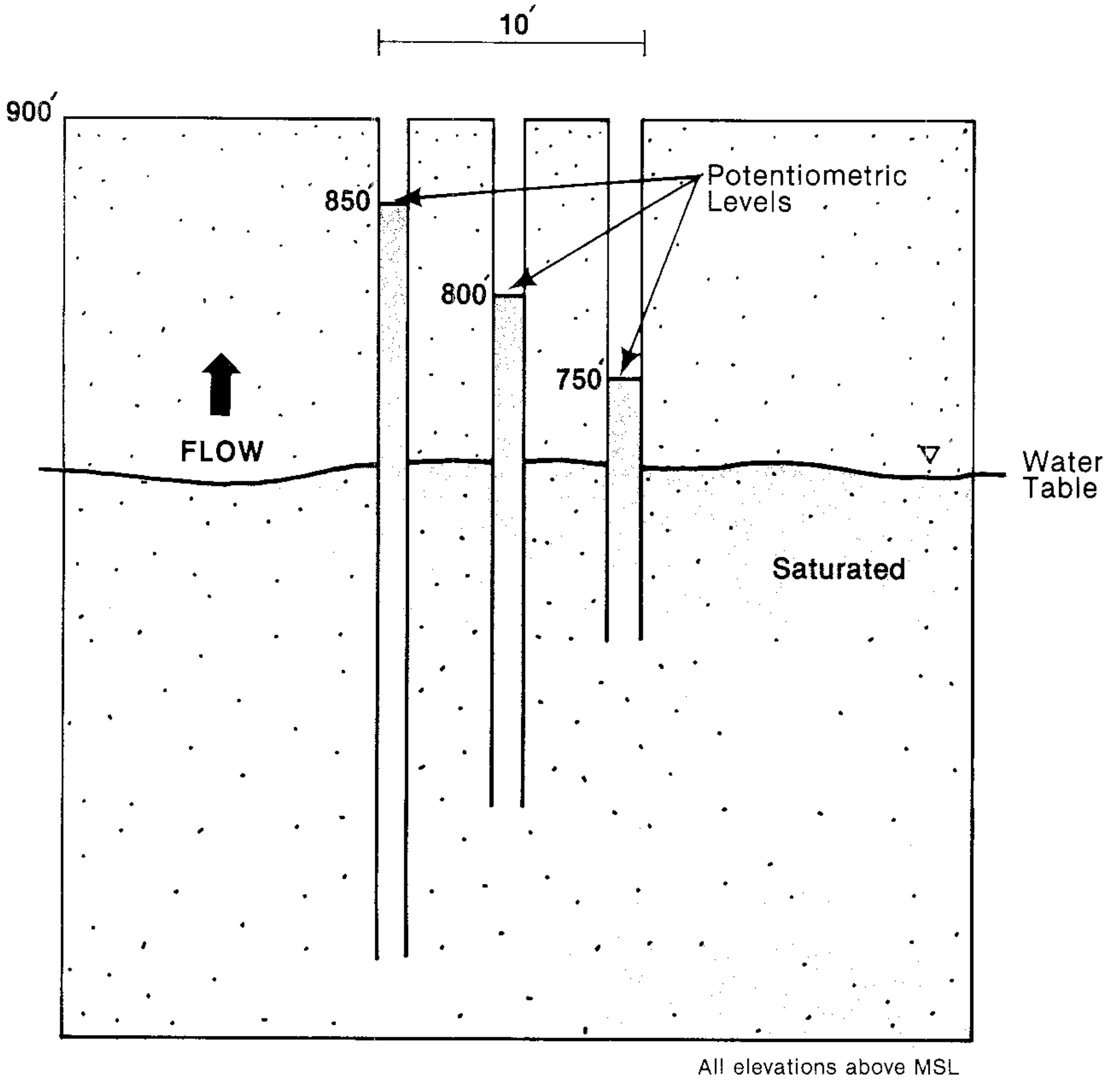
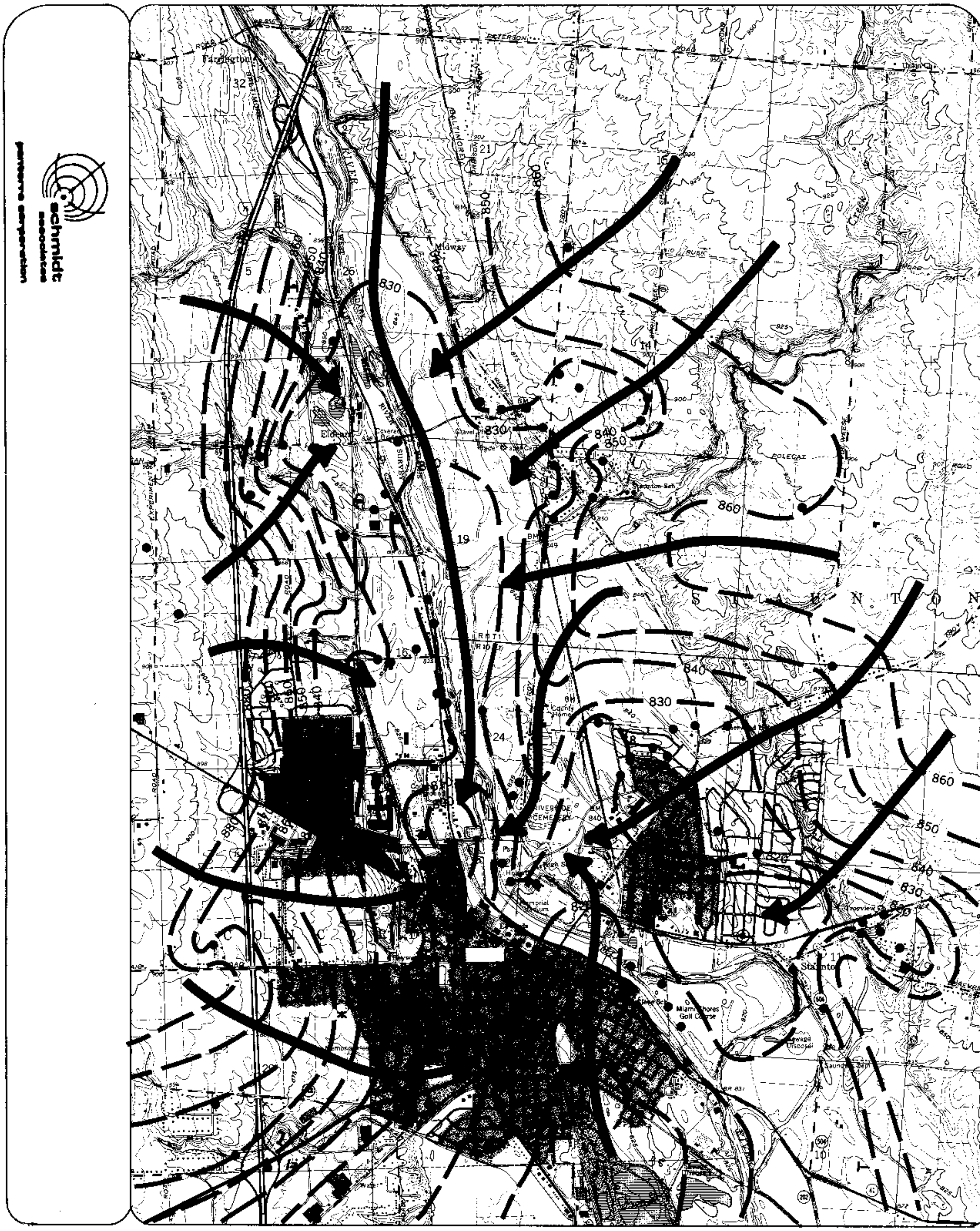


Figure 4-14. ***Piezometers arranged in a close cluster to determine vertical ground water flow.***



• Well Location

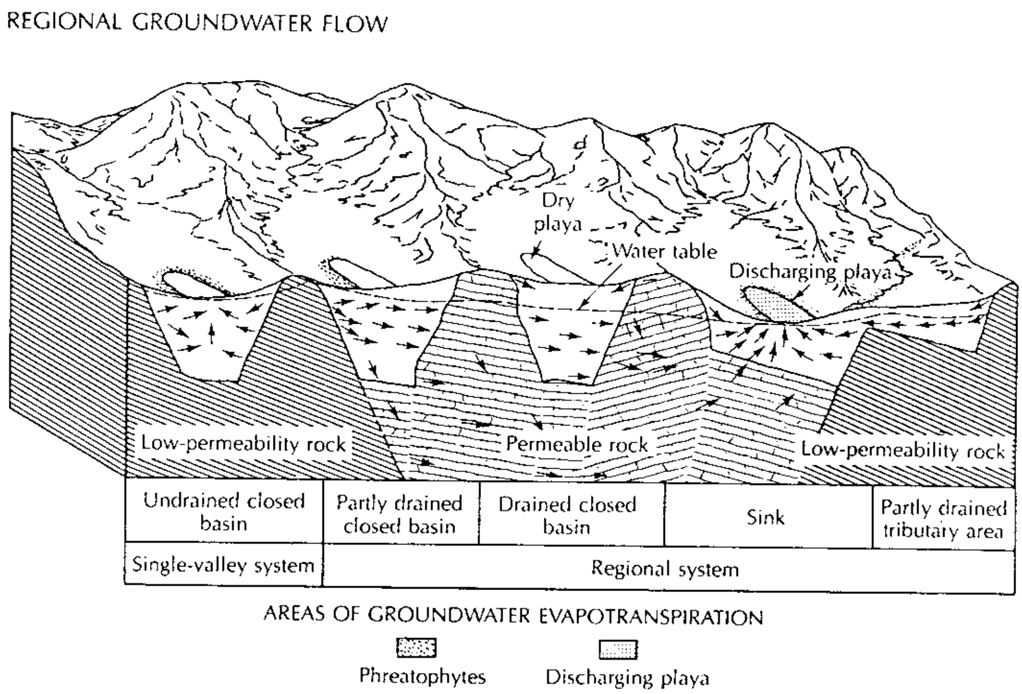
—880— Water Table Elevation Contour Line

Contour Interval = 10 Feet

← Flow Line

N

Figure 4-15. *Jefferson City water table map.*



Flow systems of the Great Basin Region. SOURCE: T. E. Eakin et al., U.S. Geological Survey Professional Paper 813-G, 1976.

Figure 4-16. ***Local and regional ground water flow.***

depression and the areal extent of the zone of influence depend upon the hydraulic characteristics of the aquifer and the rate and duration of pumping.

The zone of influence includes flow to the well resulting from pumpage, as well as flow resulting from regional gradients. Because of the difficulty in measuring small head differentials in what is really a dynamic environment, establishing the zone of influence from field measurements is usually much more difficult. Usually a zone is defined based upon calculated (modelled) values.

In homogeneous materials the shape of this cone is radially symmetrical around the well. Heterogeneous materials result in asymmetrical cones of depression. In highly permeable materials, such as clean sands and gravels where the hydraulic conductivity is high, the surface of the cone of depression has a gentle slope and the zone of influence is larger than that of a material with lower conductivity. Figure 4-17 shows the effect of permeability on the shape of the cone of depression while holding the pumping rate constant.

The steepness of the cone of depression will also vary with the rate of pumping. Lower pumping rates will create a cone that has a gentle slope, whereas higher pumping rates will create a cone that is more steeply sloped and extends down deeper into the formation.

Steady State and Transient Flow. In steady state flow, the rate of recharge to the system equals the amount of discharge. This means there is no actual fluctuation in the level of the water table. These conditions are, of course, not common in nature because of seasonal changes in precipitation. More frequently there is an imbalance between recharge and discharge resulting in transient flow conditions. When more water is entering the system than leaving, ground water levels rise. When less water is entering the system than leaving, ground water levels decline. Flow to a well can be affected by steady state or transient conditions.

For example, if more water is leaving the system than entering, after initial pumping the cone of depression will enlarge and the water table will continue to drop.

If conditions are steady state, the cone of depression will reach a certain shape and size and remain constant. The cone of depression and the corresponding zone of influence will enlarge until the points of discharge have been intercepted or captured. Flow at discharge points will then be reversed in the direction of pumping. Figure 4-18 shows a well drilled in an unconfined aquifer next to a stream and a flow net representing the pumping effect.

Let's say we have a gaining stream where the water table is higher than the stream level. When pumping begins, a cone of depression forms around the well and the water table elevation will begin to drop. The cone of depression will enlarge and eventually intercept the stream bed. Once this happens, the stream becomes a point of recharge and downward infiltration of stream water will actually be induced by the lowering of the head beneath the stream bed. This is called induced infiltration. The shape of the cone of depression will be asymmetrical and more steeply sloping on the stream side.

In many areas this type of recharge or infiltration can be induced through artificial means. Often impoundments and canals catch and hold water on the surface in the primary recharge areas above aquifers. Pumping conditions in and around these areas will create hydraulic gradients which will induce infiltration from these bodies of water into the aquifer.

Boundary Conditions. In aquifers there are often impermeable materials that can greatly affect groundwater flow to a well. Most often these are bedrock and low permeability materials such as clays and shales. For example take the case of a large buried valley bounded by impermeable shale and filled with uniform deposits of sand and gravel. If you were to put a well into the center of such a valley and start pumping at a constant rate, a cone of depression would form and depending upon the aquifer characteristics, enlarge and eventually stabilize at a constant distance around the well. The aquifer is at equilibrium at this point in time. A sudden increase in the rate of pumping will cause additional drawdown and a reconfiguration of the cone of depression. If the cone intercepts an impermeable boundary, such as a till zone, there will be a sudden increase in the rate of drawdown.

The same effect can be illustrated by relocating the well at the edge of the valley near the interface between the glacial deposits and bedrock. When the cone of depression or zone of influence reaches the valley wall, there will be an instant lowering in the water table. This will, of course, affect the amount of water that can be pumped continuously. The position of a pumping well with respect to boundaries can be the difference between a satisfactory and unaccept-

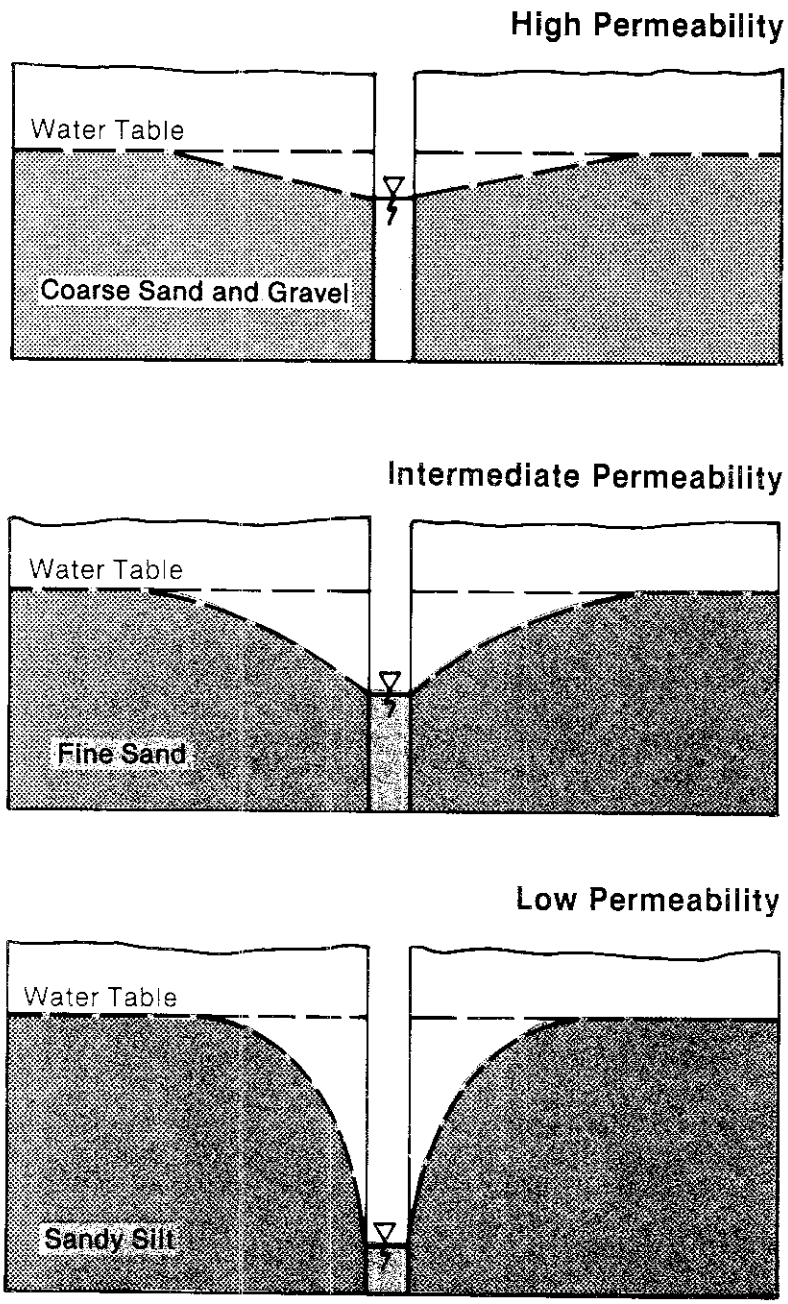
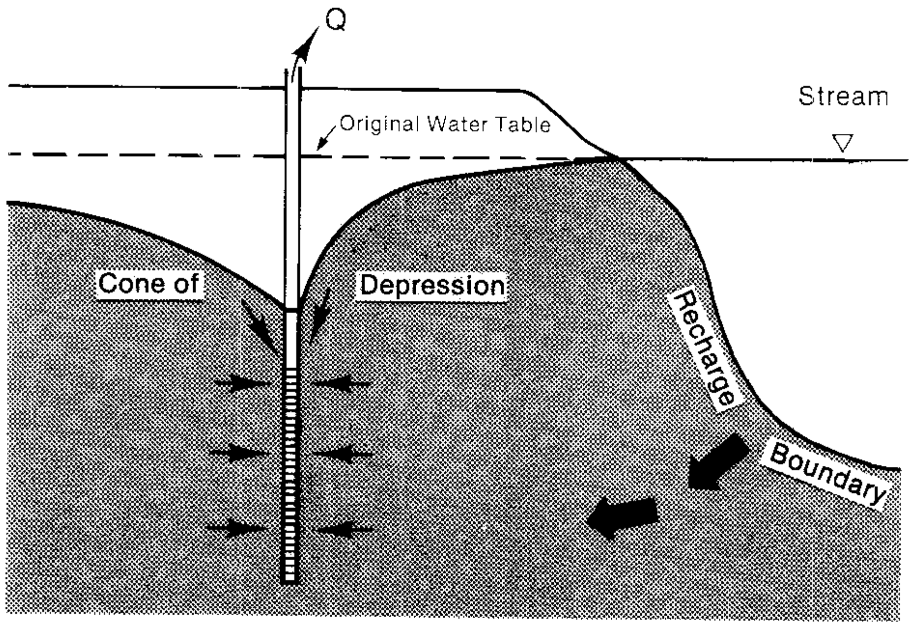
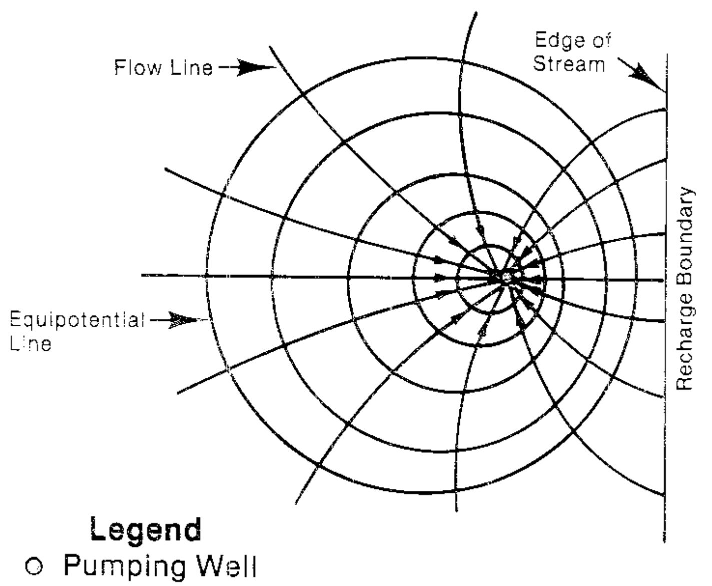


Figure 4-17. *The effect of permeability on the cone of depression (wells pumping at the same rate).*



Vertical Section Showing the Effect of Recharge on The Cone of Depression

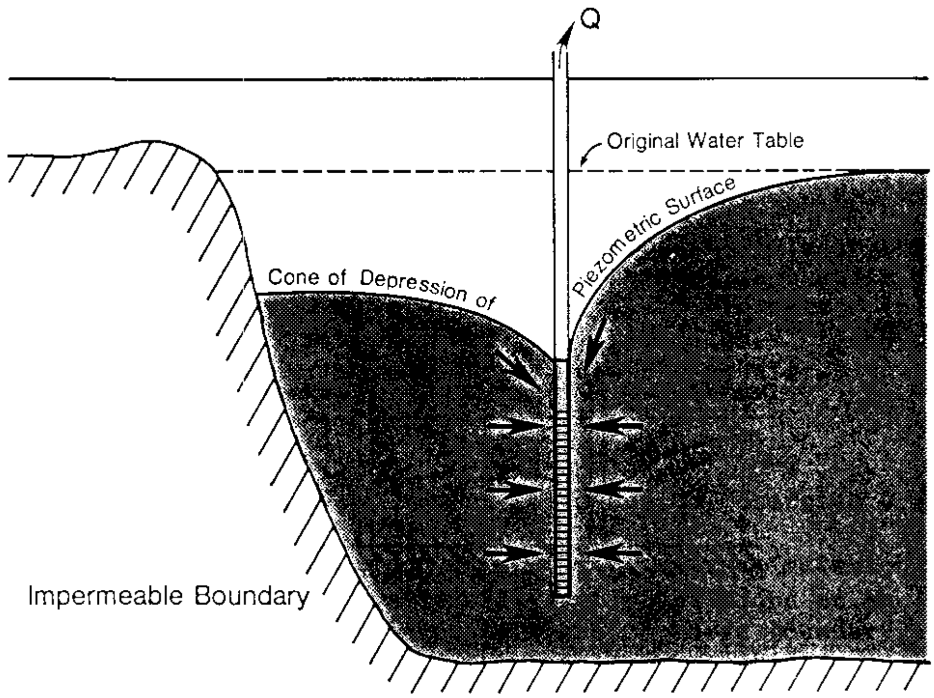


Flow Net of Pumping Well Near a Recharge Boundary (Plan View of Vertical Section Shown Above)

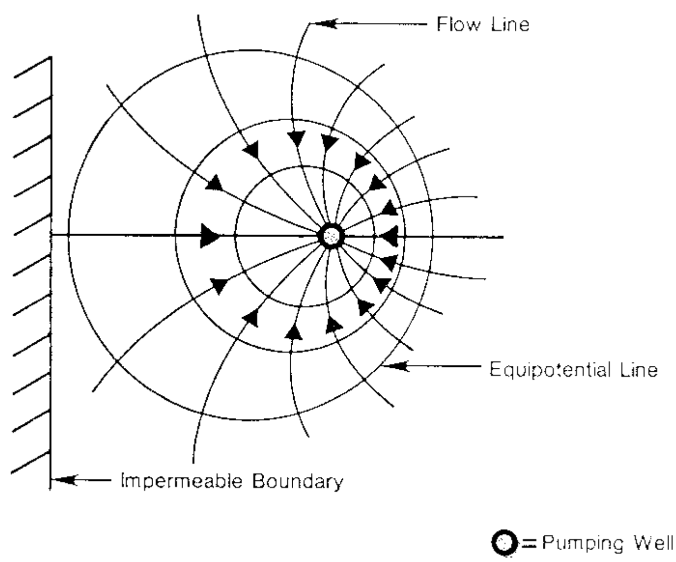
Figure 4-18. *Recharge boundary.*

able yield. Figure 4-19 shows a cross-sectional view of this boundary condition along with a schematic plan view of the associated flow net.

Effects of Multiple Pumping. What happens when two or more wells are located in an aquifer? Well, depending upon the hydraulic characteristics of the aquifer and the relative pumping rates, the cones of depression may intersect each other and have a cumulative drawdown effect on the water table. When this happens it is called well interference. Figure 4-20 shows this multiple drawdown effect along with the associated flow net configuration. Notice the direction of the flow lines.



Influence of an Impermeable Boundary on the Cone of Depression



Flow Net of Pumping Well Near an Impermeable Boundary

Figure 4-19. *Impermeable boundary.*

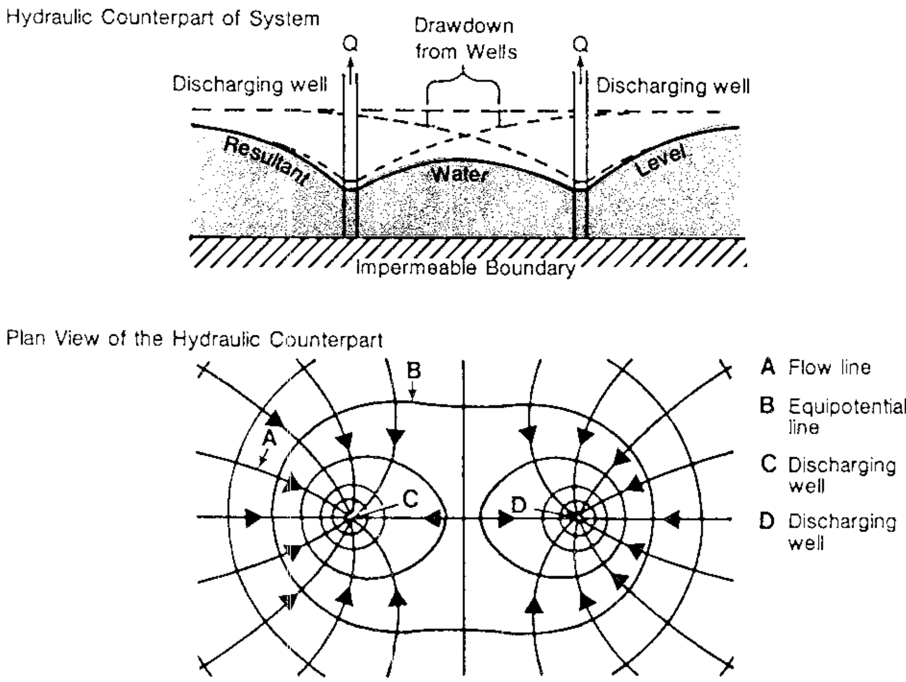


Figure 4-20. *Pumping well interference and the resulting drawdown.*

V. Aquifer Classification

Many methods have been used to classify the many different kinds of aquifers across the country. Classification may be based on potential water yield, source of water, or geologic process and material. For our purposes here, we'll divide aquifers into two main categories: unconsolidated and consolidated. These are then subdivided on the basis of geologic origin.

Unconsolidated Aquifers

Unconsolidated aquifers generally consist of loosely packed material, ranging in grain size from fine silt and clay-sized particles to coarse sands, gravels and boulders. Because of the wide range in grain size, hydraulic conductivities in this type of aquifer are highly variable.

Unconsolidated aquifers are of several different types, the most common of which are alluvial, aeolian, and glacial.

Alluvial Aquifers

In aquifers that have alluvial origins, the sediments have been deposited by flowing water in rivers and streams along channels and floodplains. Sometimes alluvial deposits are also referred to as fluvial materials.

In braided streams, the sediments are composed of coarse grained sands and gravels usually deposited under high velocity flow conditions in areas where the stream gradients are fairly steep. Fine grained particles are generally not in these deposits. Braided stream deposits tend to be heterogeneous and anisotropic. These coarser materials are often well sorted and decrease in size downstream.

Meandering river deposits include silts, clays, sands, and gravels and tend to be heterogeneous and isotropic. Along the margins of mountain ranges alluvial deposits may frequently occur in the form of alluvial fans.

Aeolian Aquifers

The second major type of unconsolidated aquifer are aeolian deposits usually composed of silt or sand that have been transported and deposited by the wind.

Aeolian sand deposits are in three places: arid environments, regions that are topographically low and flat, and areas with transportable surface sand. Sand in these environments is usually rounded, fine to medium grained, and fairly uniform in texture.

Aeolian aquifers are usually homogeneous and isotropic and have porosities ranging from 30-45 percent. Hydraulic conductivities are moderate in comparison to other aquifer materials (from 10^{-2} to 10^{-4} centimeters per second). These deposits tend to be more uniform in thickness than alluvial aquifers.

The second type of material in aeolian deposits is loess or wind blown silt. Loess is a post-glacial deposit resulting from wind-blown clouds of silt and dust. These sediments are generally deposited over large regions of low flat land. Often the particles are composed of cohesive clays and calcium carbonate.

Silt has a low hydraulic conductivity (from 10^{-3} to 10^{-5} centimeters per second). Porosity ranges between 40 and 50 percent. Permeability is low but locally may be high enough to yield domestic supplies of water. Fractures, animal burrows, and root zones often increase the vertical permeability.

Glacial Aquifers

The third major type of unconsolidated aquifer is of glacial origin (fig. 5-1). In this group are materials laid down directly by the ice and materials that were laid down by the meltwater coming off the ice.

The materials deposited by glacial processes are known as glacial drift. Drift generally includes till that is a mixture of sand, gravel, boulders, silt and clay. As a progressing glacier moves across a land surface, earth materials are moved and taken up by the ice. When the glacier retreats and the ice melts, these materials are released and deposited in an

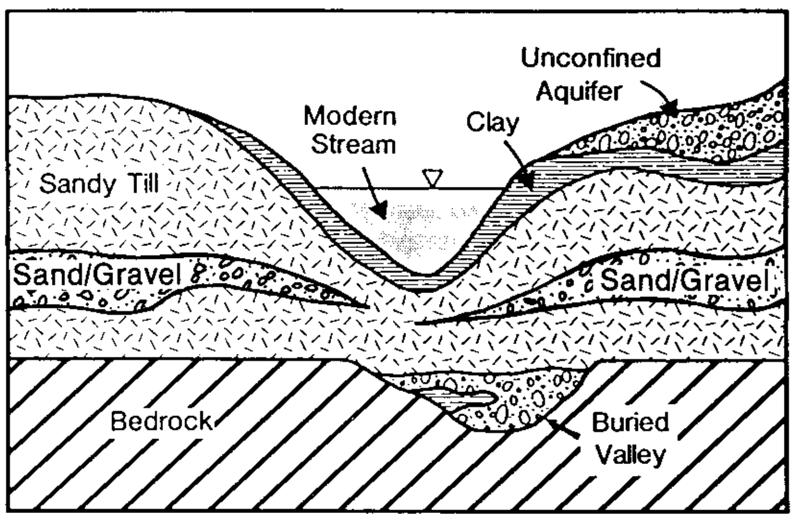


Figure 5-1. ***Occurrence of unconsolidated glacial sediments.***

unsorted fashion. Drift is often laid down in a broad till plain. Other glacial features such as drumlins and moraines are formed by deposition directly from the ice. All can develop secondary permeability through the formation of joints and cracks.

Materials indirectly deposited by glaciers are carried along by meltwater streams and slowly sorted and deposited downgradient from the ice. These materials are deposited as outwash deposits with the fine materials generally being carried away and eventually deposited further downstream. Because of their weight, the heaviest materials will be dropped out of the meltwater first. Valley-train deposits are sorted sequences of sand and gravel usually deposited along high velocity drainage routes. Buried valleys, kames, and eskers are features that most often result from meltwater deposition. The buried valley in Jefferson City is filled with valley-train deposits.

Hydraulic conductivity in glacial materials is highly variable depending on grain size and the degree of sorting. These materials are quite heterogeneous and anisotropic. Hydraulic conductivities can be high or low depending upon position in the aquifer.

Also, glacial lacustrine aquifers are possible. These generally result where meltwater lakes form below or in front of a glacier and fine materials settle. These deposits include silts, clays, beach sands and pebbles. Glacial lacustrine deposits usually have relatively low hydraulic conductivities. Sometimes the silts and clays form extensive aquitards.

Consolidated Aquifers

Sedimentary Aquifers

Sedimentary rocks are derived from physical, chemical, and organic processes. Some types resulting from physical processes are sandstones, some carbonates, siltstones and shales. Limestone, dolomite, gypsum and salt are the result of chemical processes. Some organic materials such as peat are chemically and bacteriologically broken down, heated through geologic time, and lithified to form stratigraphic sequences of coal and lignite.

In sedimentary formations that have not been overturned by folding processes, the younger rocks overlay the older rocks. These formations often show layered bedding, each layer representing a different environment of deposition (river delta, deep ocean, tidal area). Sometimes sedimentary formations are folded, bent or flexed producing a change in the angle and direction in which a formation dips. The degree of folding affects the aquifer's productivity and depth of the available ground water. In tight folds, there may be localized water supplies and deep water tables. In gentle broad folds, shallow regional aquifers often exist. Sometimes the folds are breached by erosion, producing outcrops that serve as recharge or discharge areas. Frequently these outcrops have highly permeable layers alternating with layers of rock that have low permeability such as clay and shale. Figure 5-2 illustrates the occurrence of ground water in folded rocks and the exposure of recharge areas in eroded folds.

In sedimentary rocks, faulting may govern ground water flow. Faults and fault zones can act as barriers or conduits to ground water flow (refer to fig. 4-7). Fractures, joint patterns and solution openings are also often in sedimentary aquifers. Each of these features create secondary porosity that results in high hydraulic conductivities.

Sandstone aquifers can be highly productive. These aquifer deposits often originate from floodplain, marine shoreline, deltaic and aeolian environments. The hydraulic conductivities in these materials are usually controlled by grain size, shape and sorting as well as the degree of cementation between the grains. Most sandstones are bedded which makes them heterogeneous and anisotropic on a regional scale. On a local scale these aquifers can be extremely homogeneous.

Carbonate rocks such as limestone or dolostone are important aquifer materials. Although these materials have relatively low primary porosity and permeability because of their fine grained crystalline nature, the development of secondary porosity can make them quite productive.

Terrain where chemical dissolution of rock is prominent is called karst terrain. The absence of well developed surface drainage routes is often a key indicator of this type of environment. Features such as caverns, sinkholes and underground channels are frequently formed. Several events lead to the development of karst terrains. First the carbonate rock is fractured. Then as water unsaturated with calcium and carbonate slowly circulates through the fractures and joints, erosion and chemical dissolution occurs. Cavities are enlarged by the dissolution and a complex system of interconnected openings result. As time goes on the degree of erosion and the depth to the water table increases. Mature karst systems usually have caves at different levels of saturation corresponding to the lowering of the regional water table over time. Figure 5-3 shows a cross-section of this type of aquifer environment.

Coal and lignite materials can also form sedimentary aquifers. These deposits originate from decayed organic matter that is buried and then subjected to increased heat and pressure. This type of aquifer usually yields only small amounts of relatively poor quality water.

Shale formations as a rule have quite low permeability and tend to act as aquitards. In these rocks, as in most others, permeability decreases with depth due to the compaction of the material. Usually the only occurrence of productive capacity is due to fracture features.

Igneous and Metamorphic Aquifers

Because of the dense crystalline nature of igneous and metamorphic rocks, primary permeability is low, ranging from only 10^{-6} to 10^{-13} centimeters per second. The crystalline structure is usually so dense that the void space is almost absent and porosity values are also low, sometimes as low as two percent.

Almost all ground water supplies that come from igneous and metamorphic rocks are the result of secondary porosity caused by fracturing. Fractures can be just a few millimeters to several meters in width and usually result from stresses within the formations. Because permeability decreases with depth, shallow igneous and metamorphic aquifers tend to yield larger amounts of water than deeper ones. Vertical columnar jointing patterns which form during the cooling of igneous rocks are often responsible for providing ground water recharge routes and storage space. Figure 5-4 shows the occurrence of ground water in this type of environment.

In addition to aquifers of intrusive igneous rocks formed from the solidification of molten rock material or magma beneath the earth's surface, there are aquifers that are composed of extrusive igneous rock (also called volcanics). These rocks are formed from volcanic processes at or above the earth's surface. A wide variety of features reflecting the entrapment of gas bubbles, organic matter, and ash during the rapid cooling of the lava often result in high porosity. Because of the relatively small amount of interconnecting space between the voids, however, permeability is highly erratic. Hydraulic conductivity is therefore highly anisotropic and heterogeneous. Volcanic materials that display the greatest conductivities and that are most often tapped for ground water supplies are porous lavas, breccias, and pumices.

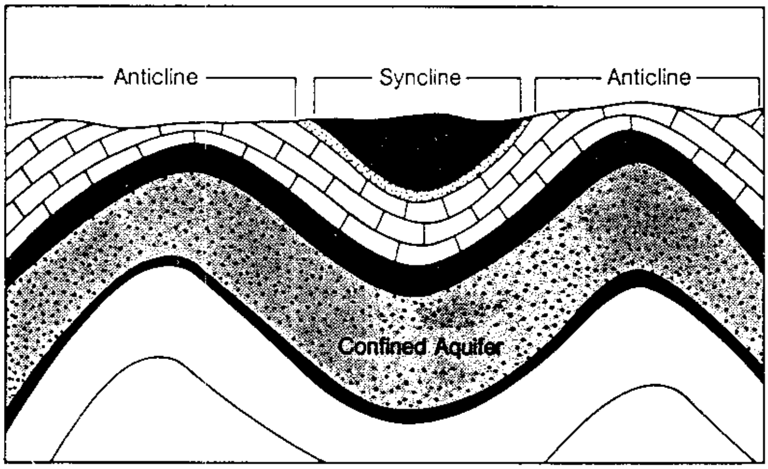


Figure 5-2. *Occurrence of ground water in folds.*

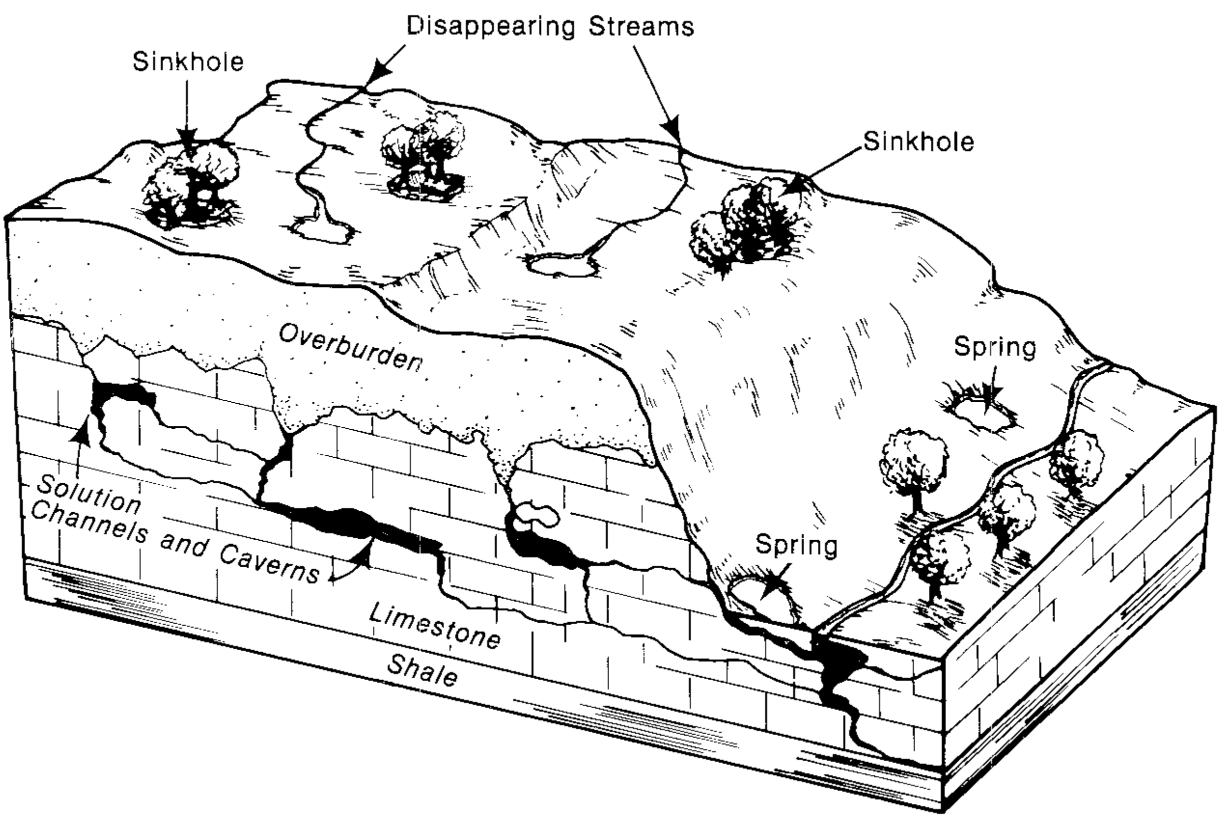


Figure 5-3. *Karst features.*

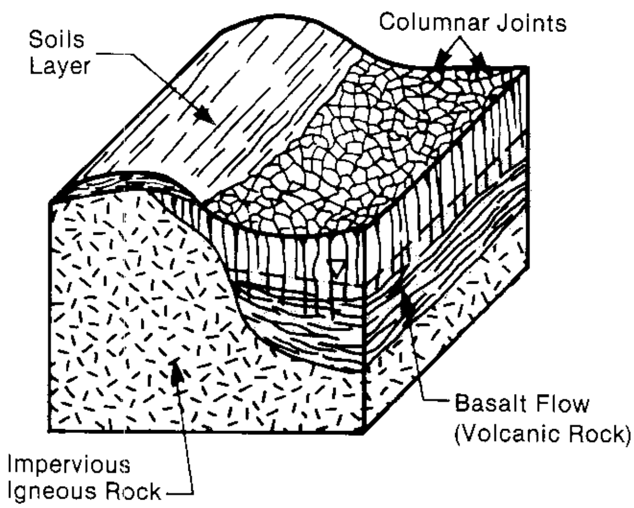


Figure 5-4. ***Ground water occurrence in volcanic rock.***

VI. Contaminant Travel in Ground Water

Once you understand the basics of ground water movement through an aquifer system, you are ready to combine this knowledge with knowledge of potential contaminant or pollutant movement through the same system. To do this you must understand the nature of various contaminant sources and the physical and chemical behaviors of the more common ground water contaminants.

Contaminant Plumes and Sources

When a volume of ground water has a high concentration of a certain solute or contaminant, the area of concentration is known as a plume. When a contaminant enters the ground water system, it spreads out in a plume with a geometry that reflects the nature of its source. There are three main categories that are used to classify contaminant sources: point sources, non-point sources, and linear sources. Contaminant sources do not always fit conveniently into such groupings; there are many instances where a source could fall into one, two, or all three of these categories.

Point sources produce contaminant plumes that extend from a single location. The most common examples of point sources are discharge pipes from wastewater treatment plants, industrial wastewater discharges, drainage tiles and storm sewer outlets, spills and leaky underground storage tanks. Any source of contamination that is localized and releases potential pollutants from a single definable location can be considered a point source.

Non-point sources of contamination are less identifiable and result in contaminant plumes that are more areal or regional. Pesticide and fertilizer application in agricultural and recreational areas, residential areas served by septic systems, and landfill leachates are common examples of non-point contaminant sources.

Leaking storm sewers, cross-country pipelines, and highway and railway routes where deicers or herbicides are frequently used, are examples of linear sources of contamination. Linearly aligned contaminant plumes originate from these sources. This category falls somewhere between point and non-point sources, coming from a definable source yet being released on a more regional scale.

Figure 6-1 shows the plume geometries of the three categories of contaminant sources. Figure 6-2 presents the classification of specific contaminant sources in plume geometries.

Contaminants usually enter ground water supplies through the near-surface materials. This means that shallow aquifers are most susceptible to contamination because they are more accessible than the deeper aquifers. Ironically, the shallow aquifers are most often tapped for their ground water supplies. These aquifers are easily contaminated through abandoned, insecure or poorly designed production and monitoring wells; induced infiltration of polluted surface water supplies as a result of pumping activities; and pesticide and fertilizer application.

Attenuation of Contaminants

The concentration of a contaminant generally decreases or in some cases may be removed from solution as it moves through an aquifer medium. This is known as attenuation. There are three processes which aid attenuation: decay, sorption, and dilution.

Some contaminants actually decompose with time as they move through the ground water. Their concentrations continually decrease as they are exposed to the aquifer medium. Examples of this would be the oxidation of wastes, chemical breakdown, pesticide breakdown, the half-life decay of radioactive wastes, and in the case of organic contaminants, the death of certain microorganisms and biodegradation of sewage.

Also, chemical processes aid in decreasing the concentration of certain contaminants. Some pollutants can adhere to the soil or rock particles by a process called sorption. Sorption is common in fine grained materials that have large surface areas such as clays, whereas coarser-grained materials have lower capacities. Under certain temperature, pH and oxidation-reduction conditions, contaminants may be removed from solution forming solid precipitates. Different chemical conditions exist in different parts of the subsurface. Above the water table in the unsaturated zone, aerobic conditions usually result in an oxidizing environment. In the saturated zone, anaerobic reducing conditions often exist favoring the solution of many substances.

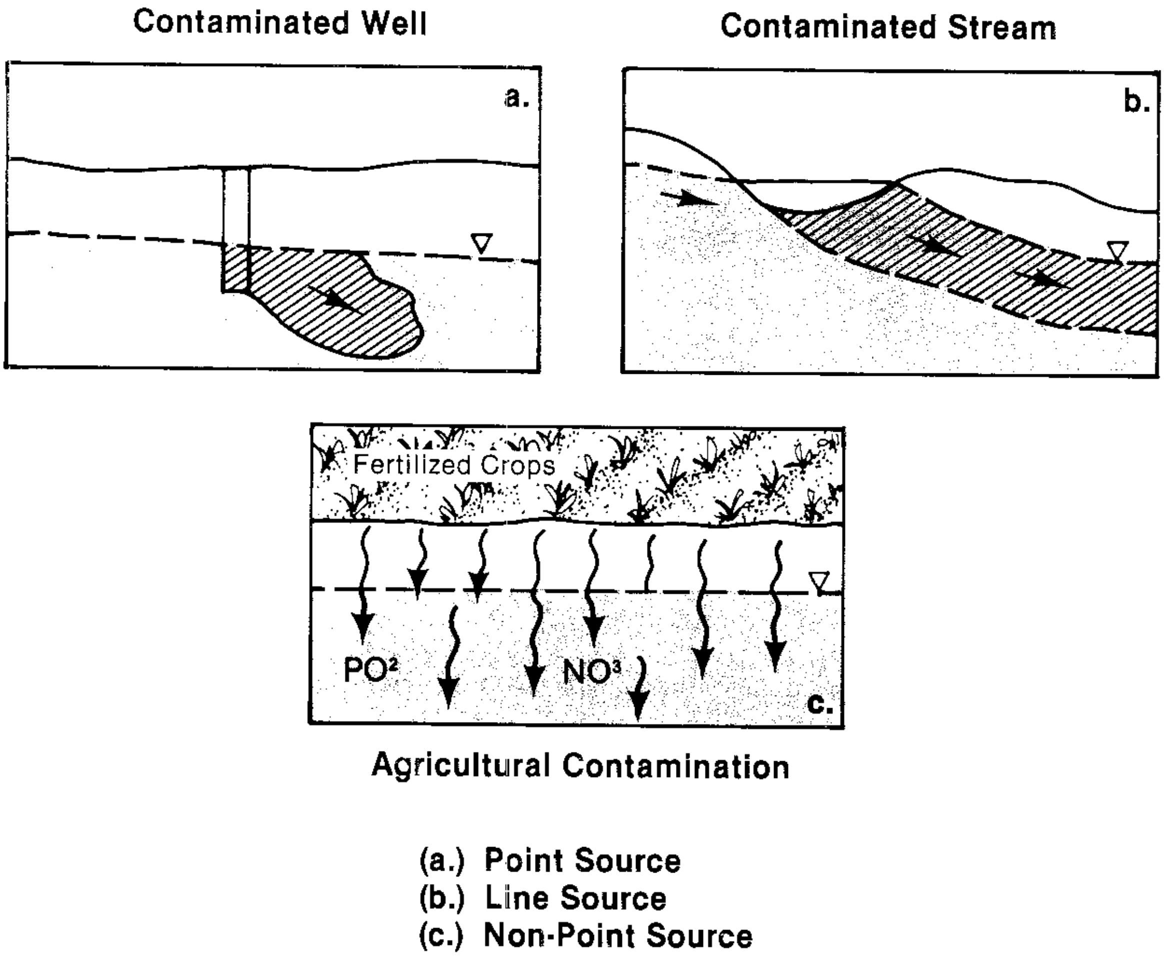


Figure 6-1. *Contaminant sources - point, non-point and line.*

Source	Typical Occurrence		
	Point	Line	Non-Point
Municipal			
Sewer Leakage	●	●	
Sewage Effluent	●	●	●
Sewage Sludge	●		●
Urban Runoff	●	●	●
Solid Wastes	●		
Lawn Fertilizers			●
Agricultural			
Irrigation Return Flows			●
Fertilizers			●
Soil Amendments			●
Pesticides and Herbicides			●
Animal Wastes (Feedlots and Dairies)	●		
Stockpiles	●		
Industrial			
Cooling Water	●		●
Process Water	●		
Storm Runoff	●		●
Boiler Blowdown	●		
Stockpiles	●		
Water Treatment Plant Effluent	●		
Hydrocarbons	●		
Tanks and Pipeline Leaks	●	●	
Oilfield Brines	●	●	●
Mining Wastes	●	●	●
Miscellaneous			
Polluted Precipitation and Surface Water		●	●
Septic Tanks and Cesspools	●		●
Roadway Deicing	●	●	●
Salt Water Intrusion	●		●
Well Contamination	●		

Figure 6-2. *Typical geometry of contaminant plumes.*

Other contaminants may be diluted by the ground water through a process called dispersion. Dispersion causes the contaminant concentration plumes to spread out downgradient from the source. The spreading of the solute leads to its eventual dilution and decrease in concentration. When the solute spreads out in the direction of the ground water flow, it is known as longitudinal dispersion. Transverse dispersion is characterized by the spreading of the solute in a direction perpendicular (usually vertical) to the ground water flow. Figure 6-3 shows how the process of dispersion affects the concentration of a tracer as it spreads longitudinally and transversely from the source.

Factors Affecting Plume Geometry

The factors which usually have the greatest effect on the spread of contamination are:

1) distance to the point of water use,
2) depth to the water table,
3) gradient and flow direction of water,
4) permeability, and
5) sorptive capacity

The shape of a plume can be determined by monitoring wells placed around the aquifer area that is known to or thought to be contaminated. The delineation of a plume hinges on the effective placement and sampling of monitoring wells. Without a thorough knowledge of the hydrogeology and the nature of the contaminants, combined with a sound monitoring approach, you could quite possibly install an expensive monitoring network and still be unable to detect a contaminant plume. We'll discuss the placement of the monitoring wells later, but for now we're going to discuss the various plume shapes and what these shapes tell us.

The characteristics and extent of a plume will vary according to different factors:

1) local geology,
2) ground water flow,
3) continuity at the source,
4) type and concentration of the pollutant,
5) human activities.

The hydraulic characteristics of local consolidated or unconsolidated aquifers can significantly affect the dispersive pattern of a plume. In highly permeable materials there will be a greater tendency for plumes to spread more extensively because of the freer movement of the ground water. Increased rates of the ground water recharge and flow will also expedite the mixing and dispersion of a contaminant plume.

In anisotropic materials such as sedimentary rocks or alluvial deposits, great differences may exist in hydraulic conductivity with direction. In these materials ground water flow and the development of contaminant plumes may be predominantly along the horizontal permeable zones. The presence of impermeable barriers such as clay lenses can divert ground water flow away from its assumed direction. If such barriers are undetected, they can pose a monitoring well location problem (fig. 6-4).

In the presence of well-developed secondary porosity, high levels of contaminants move quickly along subsurface flow routes such as solution channels and fractures. These features are difficult to locate and contaminants often move long distances without being detected by monitoring networks (fig. 6-5).

A continuous source of contamination in ground water often shows up as an enlarging plume. This may occur because the ability of the soil or rock to adsorb the contaminants has been exceeded. A plume that is decreasing in size often indicates that the discharge at the contaminant source is slowing. In fig. 6-6, a and b are the geometries of plumes under these conditions.

A plume that maintains the same size and geometry over a period usually indicates that the contaminant is being attenuated by the aquifer material or effectively diluted by the ground water flow. In this case the adsorption capacity of the aquifer has not been exceeded yet and the dilution rate is fairly constant. Figure 6-6c illustrates a stabilized plume.

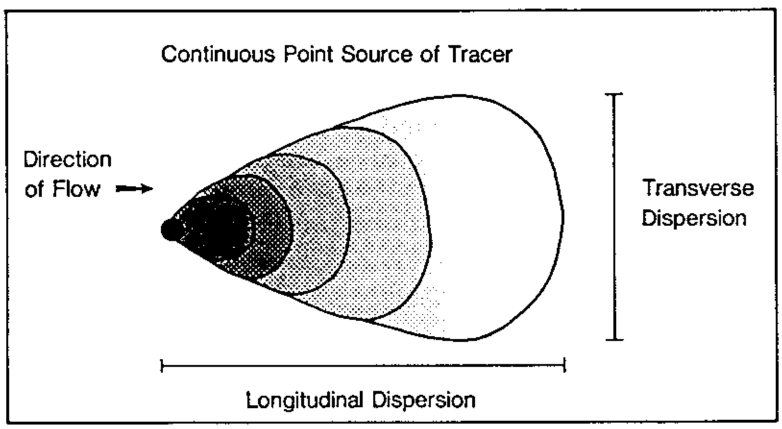


Figure 6-3. ***Hydrodynamic Dispersion.***

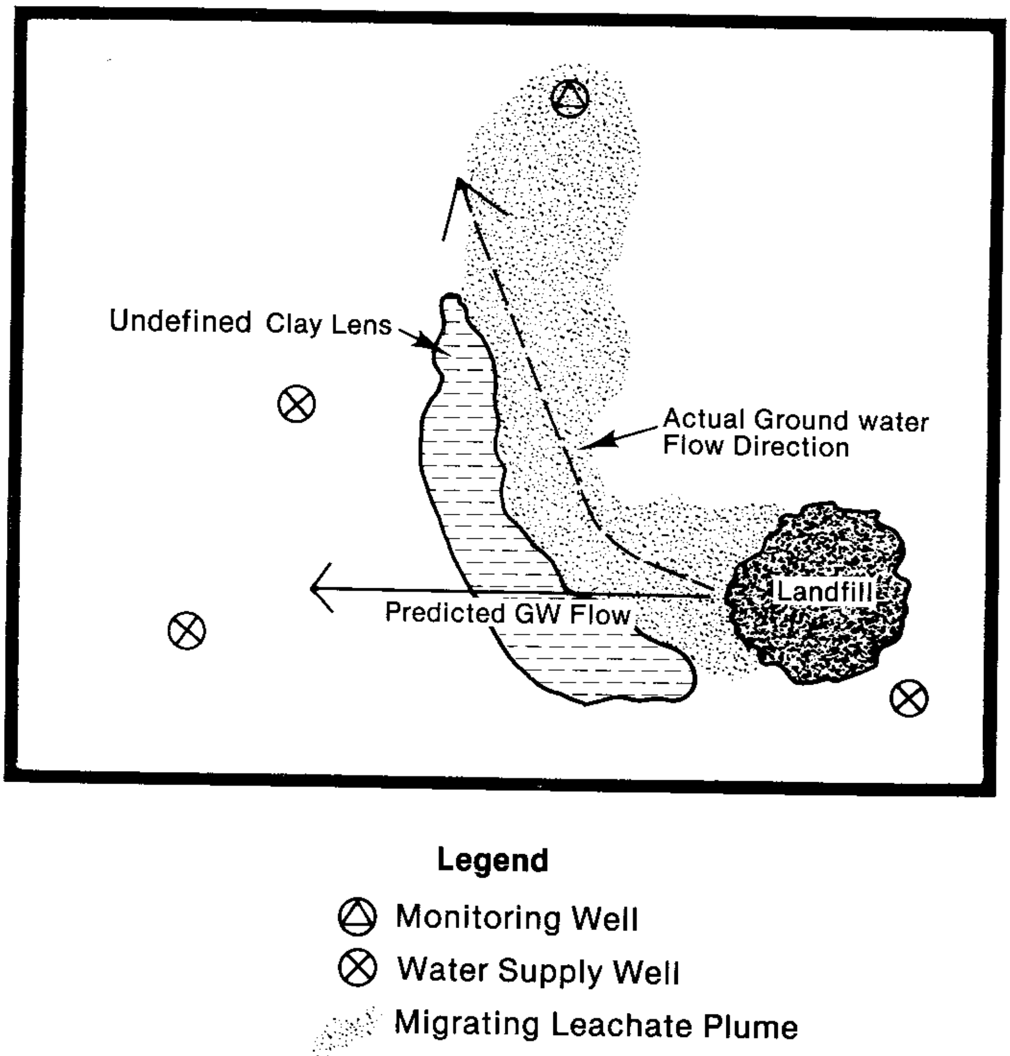


Figure 6-4. *Effect of hydrology on monitoring well effectiveness.*

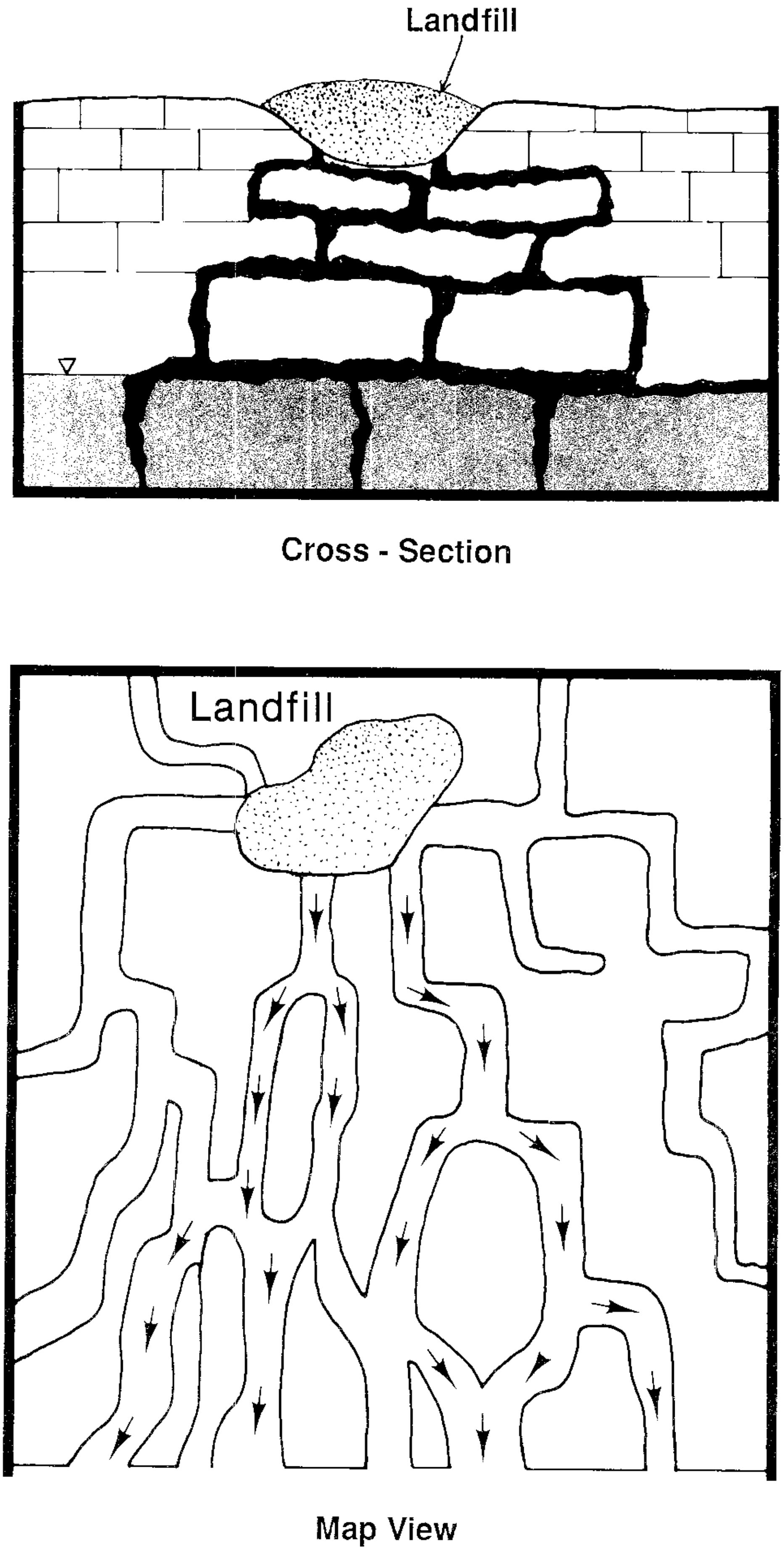


Figure 6-5. *Contaminant flow through karst enviroment.*

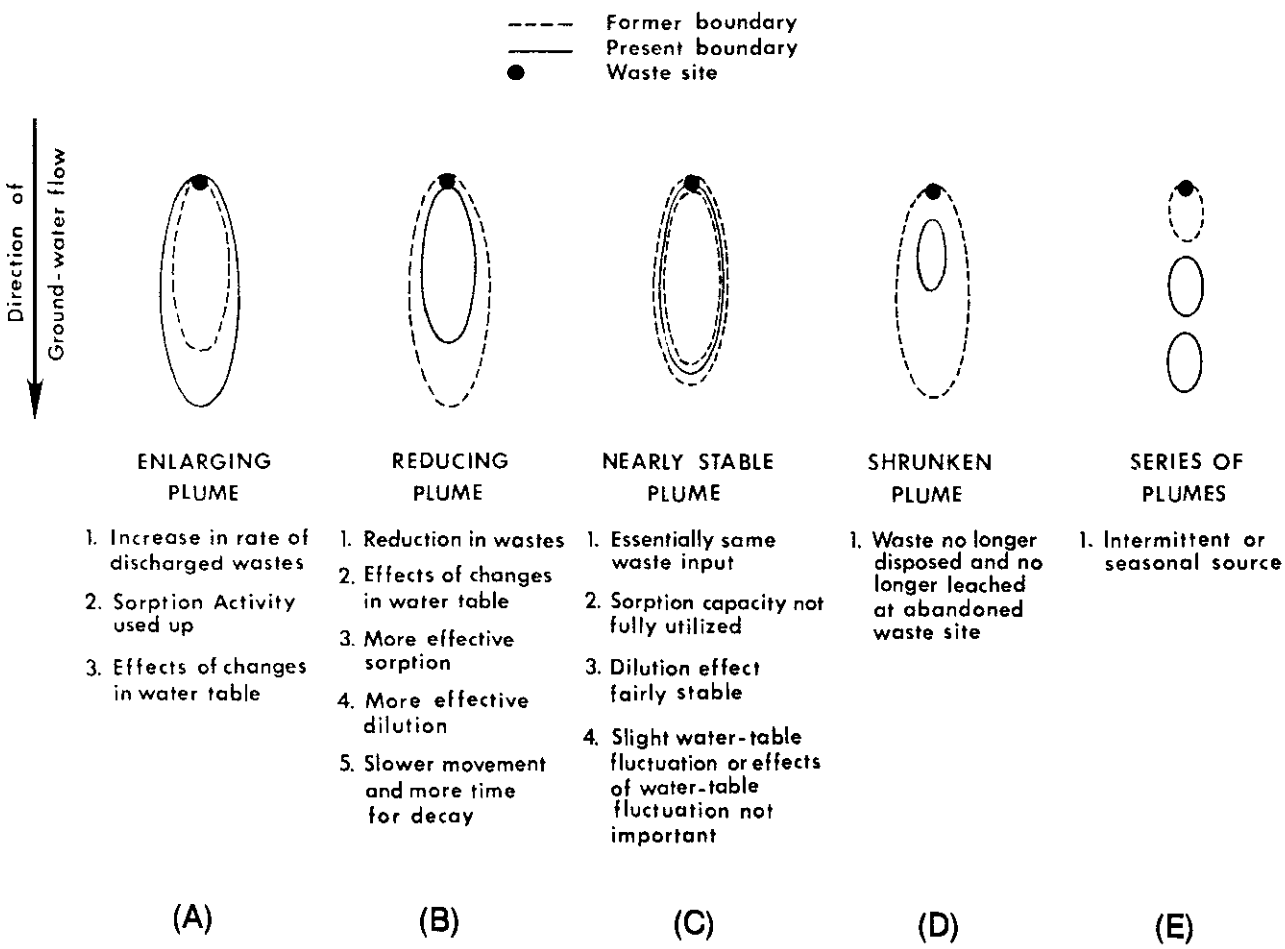


Figure 6-6. ***Changes in plumes and factors causing the changes. (Source: U.S. EPA, 1977).***

When a plume suddenly shrinks in size, it may be because the contaminant discharge has ceased and that no further leaching or dispersion is taking place. Figure 6-6d shows the before and after geometry in this situation.

Frequently a plume will seem to fluctuate, increase and then decrease in size, possibly disappear and then reappear with time, and repeat the cycle. Several isolated plumes moving along in a linear arrangement away from the contaminant source indicate an intermittent or seasonal mechanism (fig. 6-6e).

Intermittent plumes may result from artificially controlled schedules of overflow from wastewater treatment plants or industrial discharge. Natural seasonal conditions such as the rise or fall of the water table can also produce intermittent discharge plumes.

For example, little leachate is released below a landfill during the summer months when precipitation is low. During the wet season, however, precipitation and infiltration increase and accumulated leachate may flush into the aquifer. Old buried dumps may be stable for years or even decades; but when there is a season of unusually high precipitation, water tables rise and ground water suddenly comes in contact with the hazardous materials once thought to be safely disposed.

The rate of dispersion is governed by the rate of ground water flow and the characteristics of the specific contaminants. As you might expect, the density of the contaminant entering the ground water greatly affects how it will be dispersed with the ground water flow. Pollutants that have relatively low densities, lower than that of water, tend to float on the water and disperse along the top of the saturated zone. Petroleum-based contaminants and hydrocarbons often behave this way. Heavier contaminants, containing metals such as lead and mercury, often sink to the bottom of an aquifer and move along with the ground water flow at the lowest possible levels. Solutes that have densities near that of water take an intermediate path.

One way in which hydrogeologists detect unknown pollutants is to install monitoring wells screened at several different intervals or to set up clusters of monitoring wells, each well screened at a different interval, and sample. Pollutants that have different densities will be picked up at the different intervals and then identified.

If the type and hydraulic behavior of a pollutant are known, monitoring wells can be installed at the optimum levels to enhance detection. The density of the leachate determines the positioning of monitoring well screens (fig. 6-7).

Finally, pumping activities can significantly affect plume geometry and movement. Ground water production patterns may vary over time, resulting in intermittent alterations in natural hydraulic gradients. Pumping at a certain rate from one well may hold a contaminant plume in a static or decreasing position until the discharge rate at a nearby well is increased; the plume may then reverse its direction of movement. A common practice at wells where severe contamination has been detected is to continue pumping the ground water to maintain the hydraulic gradient so the contaminant plume will hold its position or shrink. At the same time a non-contaminated portion of the well field can be pumped at rates which have little affect on the established hydraulic gradient.

*　　　*　　　*　　　*　　　*

In mid-August Mike Kenton had his second encounter with Colonel Randolph Banks. Kenton had almost looked forward to hearing from the Colonel again because he had done his homework and was ready to talk to the hard-edged gentleman about ground water. Hopefully this time on more even footing. He now had a pretty good grasp on the general ground water flow patterns in the region. So, when the Colonel called to follow-up on his inquiry about the direction of the hydraulic gradient west of town, Kenton invited him over to the office that same afternoon to view the flow map he had made. Kenton had just finished re-drafting it and was pretty satisfied with his work and ready to show it off. He was also pretty confident about its accuracy and was ready to defend it against any offensive the Colonel might launch.

When the Colonel arrived he wasn't anything like Kenton had pictured him. He was short, round, and bald and bore a striking resemblance to Kenton's grandfather. He did have a commanding voice and manner however, and a handshake grip that almost caused Kenton's right knee to buckle.

Kenton led him into the conference room and showed him the flow map which was spread out on a big table. For the first few minutes there was almost complete silence as the Colonel pored over the map. From time to time the Colonel looked up at Kenton with one eye squinted. At one point the Colonel began to strut back and forth in front of the

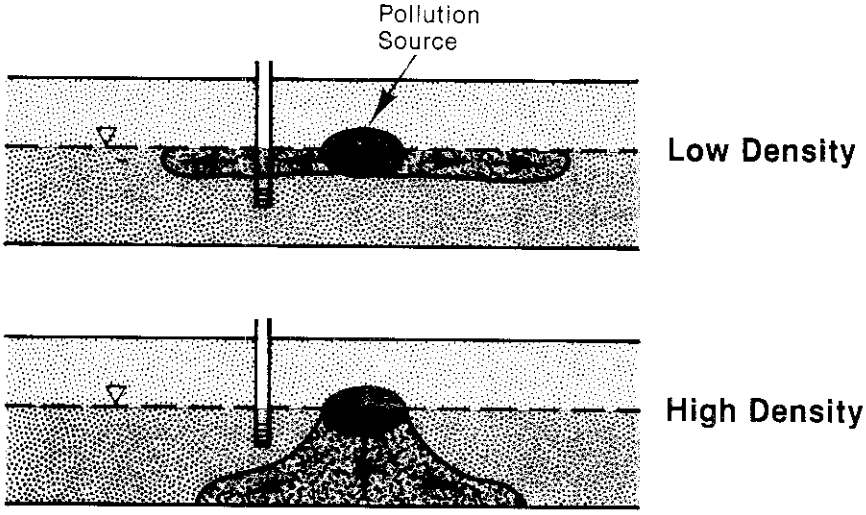


Figure 6-7. *Density of leachate affecting the positioning of the screened interval (both wells miss the plume).*

table. With Kenton standing "at ease" on the other side of the table with his hands folded behind him, the scene looked a bit like one from an old war movie—perhaps a high level strategy meeting at a command post somewhere at the battlefront.

Only the battle never came, not even a little sparring. The Colonel finally just looked up with a big grin and a nod and said "This is a damn good job young man—just the kind of information I need! If I've got the hang of this map right, it's pretty plain that my new property isn't anywhere near the Kuma Estates ground water flow path. My friends call me Buzz, what'll I call you?".

After that, the conversation really started to flow. First they discussed the property that the Colonel was thinking of buying and on which he would build a house. According to Kenton's map it was located north of the Kuma Estates area and was not directly linked to the ground water flow and problems which had been occurring there. Kenton had plotted on the map the various locations where well water problems had occurred in the past weeks. They discussed the possible shape and source of a contaminant plume with respect to the hydrogeology and ground water flow direction. Although there were no guarantees, the Colonel's lot appeared to be in an area where there were no up-gradient potential contaminant sources. The Colonel happily announced then and there that he would close the deal on the property and promptly invited Kenton to the first backyard cookout at the new place next summer.

The rest of the afternoon they talked about many things: siting the septic system, drilling a water well, the Colonel's hobbies of growing hybrid roses and birdwatching (Kenton also was an avid birdwatcher), the plight of the American farmer, Kenton's family, the upcoming football season, and of course, the growing problems with ground water contamination. The Colonel had evidently had some experience with dealing with ground water problems on some of the military installations where he had been stationed. He told Kenton some unbelievable horror stories about the contamination problems at some bases. He also had strong opinions about the lack of direction and commitment which he felt was prevalent at many levels of government in addressing environmental issues.

Kenton's first impressions had been wrong. The Colonel was not the stuffed shirt, establishment type he had expected. This man had terrific creative energy and was committed to a number of social and environmental causes. He was indeed a sincere and sensitive man who was capable of stating his opinion in a sometimes blunt yet surprisingly eloquent manner.

Before the afternoon was over Kenton had made a new friend. Little did he know that at this time next year Colonel Banks would be running for Mayor of Jefferson City on a "Protect Jefferson City's Ground Water" platform.

VII. Ground Water Resource Assessment

Ground Water Quantity

We have already touched on the idea of water budget studies at the end of Chapter 3. Although they are usually used to assess ground water quantity, they can also be applied indirectly to quality issues. For example, let's say you are concerned about the impacts of leachates from an improperly designed landfill located over an alluvial aquifer. A water budget study would be a logical first step in determining seasonal recharge in the area. By knowing when most of the infiltration and recharge is taking place, you are able to anticipate when the greatest concentrations of leachates are being flushed into the underlying aquifer. From this you can more efficiently adjust monitoring and sampling schedules and production patterns in the area.

A water budget can be simple or complex depending upon the type of system and the accuracy and amount of data available to you.

Many of the parameters used for hydrologic budgets such as precipitation, streamflow, evaporation from surface bodies of water, and runoff are measured directly. Other elements such as evapotranspiration have to be calculated indirectly.

Water budgets are most useful in determining the amount of recharge entering an aquifer. By determining the amount of water entering and leaving an aquifer, one can predict whether there is an excess of recharge. If so, some proportion of that recharge can be captured by wells. The amount of water available for use from an aquifer is not only the natural recharge; it is also the increase in recharge or leakage from the surface or adjacent strata induced by ground water development along with the reduction in discharge. Figure 7-1 shows a comprehensive checklist for the data acquisition involved in conducting a water budget survey.

Some hydrologic elements are more difficult to estimate than others. Potential evapotranspiration is one of these elements. Thornthwaite has devised a method for estimating the effects of evapotranspiration using temperature, latitude, and other climatological data generally available for most locales. Details on these methods are summarized in *The Climatic Water Budget In Environmental Analysis* by Mather, (1978).

Principles of Yield

Ground water development is based on the idea that a portion of the natural discharge that is destined to leave the ground water system may be intercepted and captured by wells and extracted for human use. Many different terms have been used to describe the amount of water that can be safely produced from an aquifer. The concept of safe yield is perhaps the most widely known and is defined as the amount of ground water that can be continually produced from an aquifer, economically and legally, without having any adverse effect on the ground water resource or the surrounding environment.

Whenever the amount of withdrawal or discharge from an aquifer exceeds its safe yield, an overdraft condition results. An overdraft is characterized by continually declining water tables or potentiometric surface levels. Sometimes this is referred to as ground water "mining." In mining, the amount of ground water recharging the aquifer never catches up with the amount being produced and the resource is simply not replaced within any reasonable amount of time (fig. 7-2). Seasonal "mining" of an aquifer (temporary overdraft) is a common practice everywhere because the annual hydrologic cycle will recharge the deficit. However, any overdraft practice should be undertaken carefully with a clear picture of the water budget.

Overpumping in many cases has severely affected the status of precious irreplaceable ground water resources. Extensive ground water development in some areas may result in the slow decline of local or regional water table levels. As the amount of production increases, water tables drop below well intakes. Competition for ground water forces the development of wells in deeper parts of the aquifer. This cycle can continue until all current supplies are depleted and there is little or no prospect of the resource renewing itself. Usually before this happens, warning signs such as land subsidence, changes in surface vegetation patterns, the dewatering of wetlands, and other adverse environmental impacts can occur. The economic cost of these impacts can be significant.

Perhaps the best known case of ground water mining is the Ogallala Aquifer underlying plains states from Nebraska and South Dakota to the arid southern High Plains of New Mexico and Texas. For many decades this alluvial aquifer

Surface Water

- ❑ Use
- ❑ Quality (See Figure)
- ❑ Amount and Distribution of Runoff
- ❑ Capacities of Lakes, Ponds, Swamps, Man-made Reservoirs
- ❑ Inflow/Outflow Data
  - current meters
  - weirs
- ❑ Return Flows
- ❑ Effect of Tributaries
- ❑ Measurement of Basin Parameters
- ❑ Streamflow Measurement Stations
  - manual gages (staff gages)
  - recording gages
  - crest-stage gages
- ❑ Seas and Oceans
  - fresh and salt water relations
  - tidal variations
- ❑ Water Import/Export Information
  - pipeline
  - tanker

Models

- ❑ Mathematical
- ❑ Electric Analog

Spring and Well Data

- ❑ Location
- ❑ Depth
- ❑ Types and Diameters of Wells
- ❑ Driller's Logs
- ❑ Static and Pumping Water Level
- ❑ Hydrographs
- ❑ Specific Capacity
- ❑ Spring and Well Yields
- ❑ Water Quality
- ❑ Present and Projected Ground-water Development and use
- ❑ Operation and Maintenance Problems
- ❑ Spacing and Geometry of Wells
- ❑ Well Design
- ❑ Pumping Rates
- ❑ Spring Development
  - location
  - type
  - geologic setting
  - collector system
  - spring hydrograph
  - quality
- ❑ Sampling Sites
- ❑ Borehole Geophysical Data
- ❑ Barometric Pressure

Cultural Considerations

- ❑ Public Utilities
- ❑ Natural Gas Facilities
- ❑ Water Supplies
  - domestic
  - municipal
  - industrial
  - agricultural
- ❑ Sewage Treatment
  - type
  - location and capacity of treatment plant
  - method of effluent disposal
  - effluent capacity
  - residue disposal
- ❑ Transportation
  - roads and highways
  - railroads
  - ships
  - airplanes

Local Drilling Operations

- ❑ Locally Available Drilling Rigs
  - size
  - types
- ❑ Locally Available Logging Services
- ❑ Drilling Practices
- ❑ Well Designs
- ❑ Well Construction
- ❑ Legal Systems
  - state
  - local

Aquifer Data

- ❑ Type
  - confined
  - unconfined
  - leaky
  - perched
- ❑ Depth of Aquifer
- ❑ Formation
- ❑ Aquifer Boundaries
- ❑ Transmissivity
- ❑ Storativity
- ❑ Permeability
- ❑ Porosity
- ❑ Hydraulic Conductivity
- ❑ Specific Retention
- ❑ Hydraulic Gradient
- ❑ Direction and Rate of Flow
- ❑ Amount and Rate of Discharge (Natural and Well)
- ❑ Amount and Rate of Recharge (Natural and Man-Induced)
- ❑ Groundwater and Surface Water Relationships
- ❑ Aquifer Models
- ❑ External Loading
- ❑ Tidal Variations

Previous Investigations

- ❑ U.S. Geological Survey
  - bulletins
  - professional papers
  - water supply papers
  - maps
- ❑ Environmental Protection Agency
- ❑ U.S. Department of Agriculture
- ❑ Corps of Engineers
- ❑ Water Resource Centers
- ❑ County Courthouses
- ❑ Universities
- ❑ Developers
- ❑ Drillers
- ❑ Private Consultants

Climatic Data

- ❑ Precipitation
  - rain gages
  - radar measurement
  - satellite estimates
- ❑ Temperature
  - extremes
  - avarages
  - length of growing season
- ❑ Evapotranspiration
  - lysimeter
  - class A pan
  - meteorological measurement

Maps, Cross-sections, Aerial Photographs

- ❑ Planimetric
- ❑ Topographic
- ❑ Geologic
  - structure contour
  - stratigraphic
  - lithologic
- ❑ Hydrologic
  - well location
  - spring location
  - water table contour map
  - piezometric surface map
  - depth to water table
  - chemical quality
  - maps of adjoining basins
  - isopach
- ❑ Vegetative Cover
  - type
  - density
  - extent
- ❑ Soils
- ❑ Geophysical Data
- ❑ Aerial Photographs

Figure 7-1. *Water budget survey data acquisition checklist.*

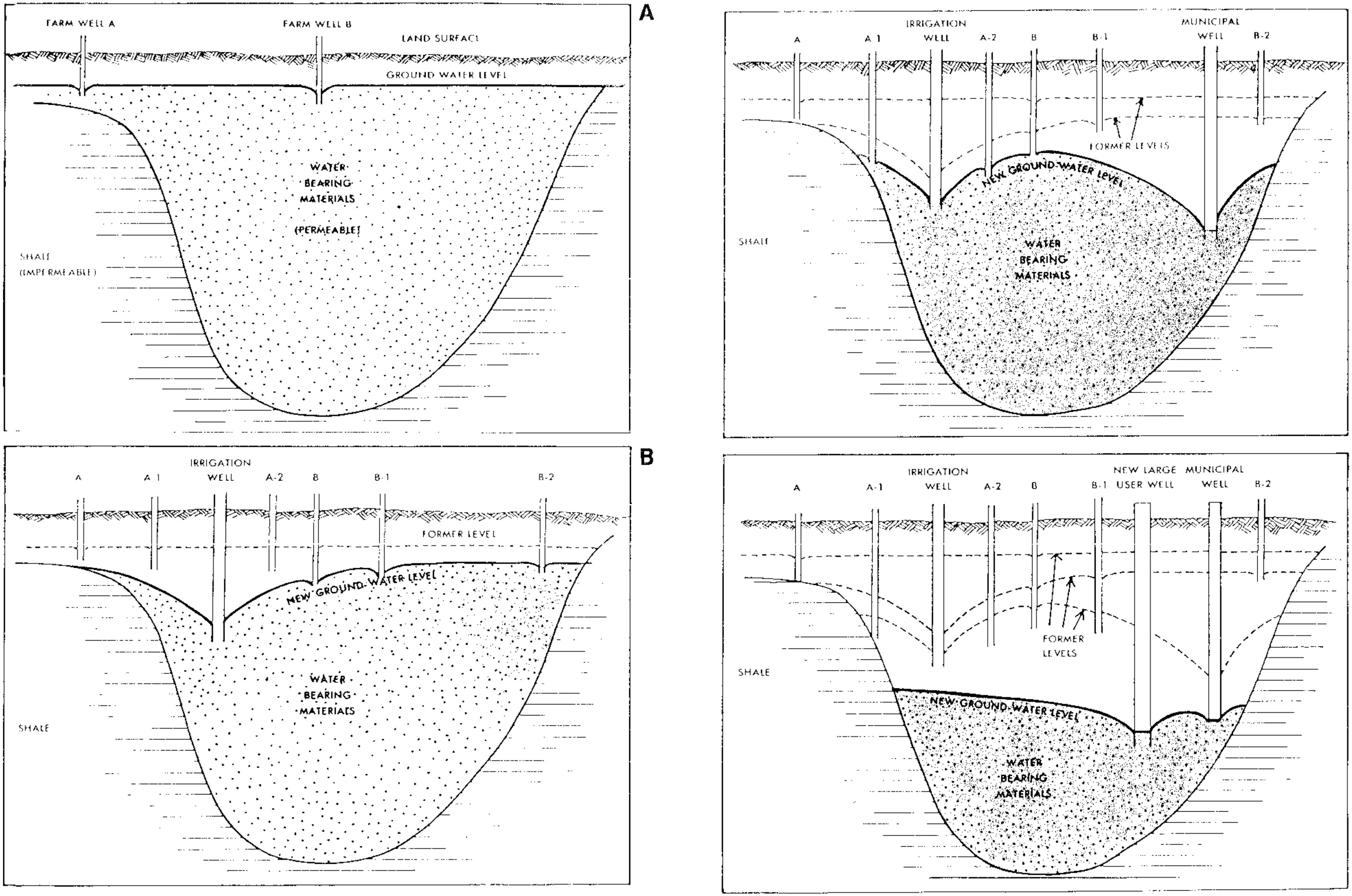


Figure 7-2. *The effects of ground water development on water tables.*

has been tapped as a source for irrigation water to support the region's extensive agricultural activity. In some areas the recharge to this aquifer has fallen behind the amount of water that has been traditionally produced, which has lead to continually declining water table levels. Because the safe yield has been exceeded in some areas, the future agricultural and industrial development potential of this region is in great jeopardy.

Another common problem encountered when safe yield is exceeded is that of salt water intrusion. This occurs in coastal or oceanic island areas or in regions that are underlain by relatively shallow volumes of saline water. Because of its lower density, freshwater "floats" as a lens upon saltwater in an aquifer. The volume and shape of the lens is dependent upon the amount of recharge and the rate of mixing at the freshwater/saltwater interface. Overpumping can cause saltwater to upcone or intrude upon the freshwater lens rendering the freshwater unusable. Figure 7-3 shows the upconing and intrusion of saltwater in a coastal aquifer. The natural integrity of the lens to re-establish itself may take many years. One must pattern production so that ground water is "skimmed" from the lens at a rate that does not adversely alter its shape.

Other concepts similar to safe yield such as optimal yield and sustained yield are frequently used to define production limits. These differ mainly in the definitions of "adverse effects" and in how liberal or conservative one wants to be in the use of the resource.

The Role of Pump Tests

Hydrogeologists and engineers use many different methods to determine how certain types of aquifers are going to respond to pumping. They also quantify localized aquifer characteristics.

Some information can be gained simply by analyzing the physical characteristics of the aquifer material under laboratory conditions. However it is more useful to be able to accurately assess the hydraulic and yield characteristics with pump tests under actual field conditions.

In pump tests, pumping is either carried out at a constant rate or at an increasing rate while water measurements are being taken at surrounding observation wells and in the pumping well. Sometimes multiple well pump tests are performed to determine the effect of several wells pumping in an area.

Although a soil conservationist will probably never need to perform more comprehensive pump tests, it is helpful to be able to do discharge or field tests and to know something about other kinds of tests, what they can tell you and who does them. You may need to consult a hydrogeologist to assist with these.

Several different types of pump tests can be performed for different reasons. Well drillers installing wells for private residential use frequently perform simple, short-term pump tests. The drillers are most interested in estimating the amount of yield at a specific localized well site concerning its predicted demand.

When investigations are being conducted for well field development, contamination studies, or regional ground water studies, you must accurately assess the aquifer characteristics under varying and long-term conditions. Then, hydrogeologists and engineers may use more involved pump tests.

Perhaps the simplest pump test is known as a bailer test. When the well has been installed and developed, the water sitting in the well is bailed out. The rate of withdrawal would be recorded and the drawdown of the water table noted. After a certain amount of bailing the water table will usually stabilize, giving some indication of the amount of water that can be extracted at that rate of withdrawal. By mathematically analyzing drawdown versus time data, parameters such as hydraulic conductivity, transmissivity, and yield can be determined.

Another type of test is called the pump-in test. In this case, instead of withdrawing water from the well, an amount of water is added to the well. The casing is filled to a certain level and is maintained at that level while water enters the aquifer. The data obtained can be used to mathematically calculate aquifer parameters.

Constant rate tests are another type of test that are frequently used. This test involves the monitoring of one or more observation wells surrounding the pumping well. While water is withdrawn from the pumping well at a constant rate, the water table level is recorded at the observation wells at certain time intervals. In this type of test, both the drawdown data and the recovery data, which is the rate of water table rise after pumping stops, are collected. A variation of the constant rate test is known as the step-drawdown test. Here the the pumping rate is increased at predetermined

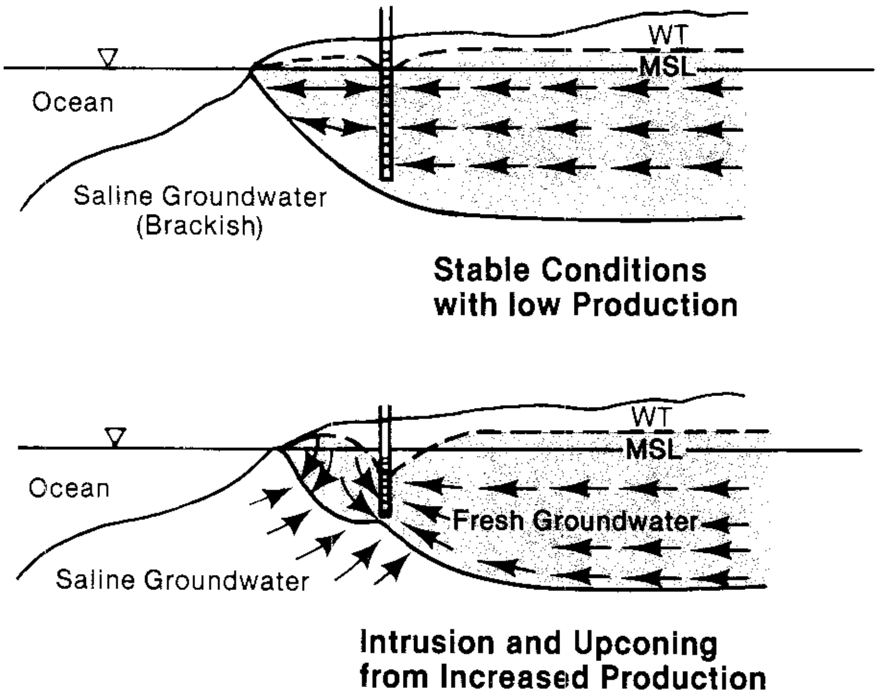


Figure 7-3. *Active saltwater intrusion.*

intervals. The storage capacity and the transmissivity of the aquifer under different pumping rates can be determined with these tests.

Most ground water books and technical manuals detail these different types of pumping tests; they include which tests are best under certain conditions, how they are performed, data collection and mathematical analysis, and their interpretation. Some pre-existing pump test data are usually available for most areas. Engineering firms, drilling contractors, university geology and engineering departments, local health and utilities departments, state EPA's and departments of natural resources, and federal agencies such as the USGS, SCS and USEPA are good places to start in finding this kind of data.

Ground Water Quality

Depending upon your area of the country, there will be variations in the natural chemical characteristics of the ground water. The different ground water chemistries are a reflection of the surrounding geology and aquifer materials, as well as the other parts of the hydrologic system such as the atmosphere and surface water environments.

Water entering the ground will naturally react with the rock and soil materials, taking into solution some of the various elements making up these materials. Often the concentrations of these constituents depend upon the rate of the ground water movement and the amount of time the ground water is able to react with the aquifer materials.

Concentrations of total dissolved solids usually increase with depth in aquifer formations. At depth, low pH and oxygen deficient conditions usually prevail, which favor the solution of many chemical constituents. Ground water at this level is also not exposed to the degree of mixing in shallow zones. This means slower movement and longer residence times. Figure 7-4 presents a summary of the principle constituents in natural ground water. Keep in mind that the normal levels of these constituents vary widely with location.

In the Jefferson City region the ground water is typically high in iron, carbonate, bicarbonate, calcium, and magnesium, which reflects shale and limestone bedrock.

Water Quality Standards

Different quality standards for ground water are determined by its intended use. Certain constituents in the ground water that may be acceptable for agricultural uses may not be acceptable for public drinking water or municipal uses. National water quality standards are set by the USEPA. Each state has the responsibility for setting its own standards; the EPA standards are the minimum requirements.

The three broad categories of ground water use are: municipal, agricultural, and industrial. Municipal standards are usually divided into two groups: primary and secondary standards.

Primary standards include drinking water standards that are based on the known toxicity of compounds at a consumption level of 2 liters of water per day. These standards may be established based upon esthetic criteria such as the removal of iron, sulfate or calcium, or they may be based on public health criteria such as the removal of harmful bacteria and chemical compounds. Secondary municipal standards include the standards that are set for sewage effluent which may be discharging into the environment.

Two main categories for agricultural standards are: irrigation and livestock. The suitability of ground water for irrigation depends upon the particular crop and the characteristics of the soil. Plants intolerant of high salinity conditions in the soil need to be irrigated with low salinity water. For livestock, ground water quality standards are usually lower than that required for human consumption. Different animals depend on different quality levels of drinking water. Recent trends in these standards are changing, however, toward the same level as that required for human consumption.

Water quality standards for industrial purposes vary widely. Some industries require that water quality be very constant in terms of certain chemical parameters. Generally, lower quality water can be used in many industrial processes. However, if the quality fluctuates a great deal, the water may begin to precipitate out unwanted minerals or chemicals. For this reason, water containing large concentrations of carbonate, magnesium, sulfate, and calcium may be unaccept-

Constituent	Primary Natural Source	Effect on Use of Water
Silica (SiO_2)	Feldspars, ferromagnesium and clay minerals, chart opal	Forms scale on boilers in the presence of Calcium and magnesium
Iron (Fe)	Igneous rocks: amphiboles, micas, magnetite, ferrous and ferric sulfide Sandstone rocks: oxides, carbonates, sulfides	May cause turbidity, stains and may impart an objectionable taste or color to foods or drinks
Manganese (Mn)	Soils and sediments, biotile, horn blende	May cause objectionable taste or stain objects
Calcium (Ca)	Amphiboles, feldspars, gypsum pyroxenes, aragonite, calcite dolomite, clay minerals	Calcium and magnesium combine with bicarbonate, carbonate, sulfate and silica to form scale on boilers
Magnesium (Mg)	Amphiboles, olivine, pyroxenes dolomite, clay minerals, magnesite	
Sodium (Na)	Feldspars (albite) clay minerals, evaporites	May cause foaming which accelerates scale formation and corrosion in boilers
Potassium (K)	Feldspars, feldspathoids, micas, clay minerals	
Carbonate (CO_3)	Limestone, dolomite	Together with Ca and Mg forms scale on boilers
Bicarbonate (HCO_3)		
Sulfate (SO_4)	Oxidation of Sulfide ores, gypsum, anhydrite	May form scale on boilers
Chloride (Cl)	Evaporites	Imparts a salty taste. Food processing, textile processing, paper and rubber manufacturing require 250 mg/l or less.
Fluoride (F)	Amphiboles (hornblende), apatite, fluorite, mica	0.6 - 1.7 mg/l beneficial effect on tooth decay $>$ 1.5 mg/l can cause mottling or disfiguration of teeth
Nitrate (NO_3)	Plant debris, animal excrement	May cause bitter taste or physiological distress if $>$ 100 mg/l
Dissolved Solids	All mineral: dissolved in water	$>$ 500 mg/l not desirable for drinking • 300 desirable for industry use

Figure 7-4. *Summary of principal constituents in natural ground water.*

able for use in certain industrial operations because the precipitates or "scale" that may build up in pipes and boilers. Where ground water is just used for cooling purposes, the quality of the water may not be of as much concern.

* * * * * *

Ground Water Contaminants and Sources

Mike Kenton rolled out of bed early on this overcast day in the third week of August. He wasn't going to let the weather get him down because today was a special day. Today was the first day of the Kuma County Fair. Today and for the rest of the week he was doing what they refer to down at the office as "riding the brochure table down at the fairgrounds." Others might think it a dull way to spend a week, but not Kenton. For him it was a working vacation. All he had to do was occupy the SCS tent down at the fairgrounds, hand out brochures, register people for the roto-tiller drawing and answer questions about the work the SCS was doing in the region. It would be a laid back week; there were no phones to answer, and best of all it was in one of his favorite places—the fairgrounds.

As a kid, more than 20 years ago, he had spent 1 week each summer literally camped out at the fairgrounds. Back then he was in 4-H and he and his brothers, John and Bill, would spend that week tending a couple of Black Angus steers that their dad had cut from the herd for them to raise, halterbreak, show, and sell. Back then it was a real adventure for them to live down there all week—surviving on nothing but sausage burgers, sugar waffles, and lemon shakes—farmboys living by their wits in the big city!

He had gotten to the fairgrounds extra early today, hours before he actually had to be there. He liked the fair in the morning—the smell of homemade waffles coming from the Methodist church dining tent and watching the 4-H kids tend to livestock.

The air was muggy after several rain showers during the night, not a lot, but just enough to settle the dust and make some small puddles. As he walked down the fairway heading for the SCS tent Kenton couldn't help but notice some things he had never noticed as a kid: the incredible amounts of trash, the buckets of oil that had been spilled underneath the rides and the piles of manure that were accumulating outside of the barns. He also saw what they used to call the "mosquito truck" making its rounds, spreading a fog of insecticide intended to keep down the fly and mosquito population. He wondered how much of the chemical was falling directly to the ground. He looked down and saw an oily residue floating on the surface of a puddle. . . .

Suddenly the rain began to fall again, this time pretty hard. He ran and took cover under the first tent awning he could find. He stood and watched it rain, noticing the puddles start to get bigger and then connect into a single stream running down the fairway, carrying with it who knows what kinds of chemicals.

His trance on the water was broken by a voice from behind him . . .

"Really comin' down, huh?"

He turned to find a vaguely familiar face. It was the woman from the health department, Carin Stevens, who he'd met more than a month ago out at the Johnson well incident. Only now she looked different. He hadn't noticed that day when she was sloshing around trying to get her first water sample, but she was very pretty. Kenton, caught off guard, now realizing he was in the health department tent (they were doing free blood pressure screenings at the fair that week) said hello while brushing his wet hair over the thinning spot on the top of his head.

"I've been meaning to call you," she said.

"Oh, yeah?" he mumbled, noticing her gorgeous blue eyes and seeing her smile for the first time.

"Yes, to give you the results of the water analyses from a few weeks ago."

"Oh," he replied, realizing that the conversation was going to be in reference to ground water. She pulled out her briefcase from behind the table and handed him some papers.

"Anything unusual in them?" he asked.

''Moderate nitrate levels for starters, but look here,'' pointing to a specific column. ''Extremely high concentrations of trichloroethylene and something called 2,4,5-T, not only in the Johnson well, but also in the other two wells out in Kuma Estates.''

Kenton understood that the nitrates could be coming from non-point fertilizer or septic sources, but he wasn't sure about the other two chemicals. He knew the 2,4,5-T was a herbicide and that was about it. They sounded serious and he'd have to look them up.

They talked about the problem for a moment, then about the weather, and then about each other. Just long enough to find out that they had some things in common. She was even a golfer! He mentioned that maybe before the summer was over they could get together for a round or two. He was surprised when she told him just to give her a call. As the rain stopped he asked her if she'd like to meet later for a sugar waffle and a lemon shake. She smiled and eagerly said yes. With that he went on his way, thinking about her smile as he dodged the stream of water, oil, and who knows what flowing down the fairway.

* * * * * *

Some sources define the words ''contaminant'' and ''pollutant'' separately. Here, however, as in most current day situations, they are both used interchangeably in reference to any solute that is introduced into or activated within an aquifer and which reaches an objectionable level. A contaminant has the potential of rendering an entire aquifer useless and creating public health hazards through ground water toxicity or the spread of certain diseases.

When dealing with ground water contamination, many important questions need to be asked. First of all, what constituents are natural to the ground water environment in the specific area? What are the specific contaminants and what is the associated health risk? What are the sources of the contaminants? How do they behave once they have entered the aquifer? What is the best way to monitor their behavior?

It is impossible to detail the specific characteristics of all the various substances that may pose threats in ground water systems; however, there are a few common broad groups which are worth mentioning.

Pathogenic Organisms

Ground water can play a significant role in the transmission of certain types of infectious bacteria, viruses and protozoans. Often the organisms involved are in sewage wastewater. Although pathogenic bacteria are the most common, tapeworms, cholera, hepatitis, and dysentery are also carried in sewage effluent. Usually pathogenic organisms are a result of improper sewage disposal practices. Many of these organisms are able to survive under extreme conditions such as freezing temperatures and the presence of certain disinfectants. Chloridation is often used to kill such pathogens and is usually effective, but not in all cases.

Bacteria that inhabit the intestinal tract of man and other mammals are known as coliform or E. coli bacteria. These bacteria are harmless and are indicators of the presence of pathogenic organisms. County health departments usually focus their water analyses on the presence of these organisms.

Organic Compounds

This category of compounds includes a list of over two million chemicals that are used daily in modern industrial, commercial and domestic applications. Of this number, more than 1500 are suspected of being carcenogenic. While many are known to exist in ground water supplies in trace amounts, their safe concentration levels are largely unknown.

Perhaps the most widely used organic chemicals are the chlorinated hydrocarbons. These chemical compounds are often used in pesticides and herbicides. Many of these substances such as 2,4,5-T, which contains a highly lethal substance called dioxin, have proven to be extremely persistent once introduced into the environment; also, they have toxic effects on human and animal populations not directly targeted in its initial application. Although the use of some chlorinated hydrocarbons has been discontinued or greatly reduced because of their environmental impact, for example DDT, heptochlor, and chlordane.

Other organic chemicals such as trichloroethylene (TCE), toluene and chlorobenzenes are extensively used as industrial and commercial solvents, degreasers, and cleaning fluids. These substances may also be in household chemicals products.

Also included in the category of organic hydrocarbons are fuels and related petroleum products. When improperly stored or handled these substances can leak into ground water and render drinking water supplies unfit for consumption.

Inorganic Compounds

The occurrence of excessive amounts of constituents such as chloride, sodium, calcium, nitrate, phosphorus, selenium, magnesium, sulfate and potassium in ground water may have a wide range of adverse health effects on human and animal populations. The possible health consequences may vary from minor gastrointestinal irritations to serious renal or cardiovascular disease.

Metals

Elements such as lead, tin, copper, iron, cadmium, mercury, and arsenic in excessive concentrations can be potentially toxic in ground water supplies. Similar to the other categories of substances discussed above the effects of metals can be quite extensive, ranging from stunted growth in crops to severe blood, bone and organ disease in humans.

* * * * * *

Meanwhile back in Jefferson City, Mike Kenton was hard at work. He had made some calls and done some reading and had found out something about Trichloroethylene and 2,4,5-T. The chief of the southwest district office of the state EPA had put him in touch with the organic chemical specialist in the state office and a call to the College of Agriculture yielded a contact with two faculty members who were doing research on pesticides. In addition to giving him some useful details about the whole spectrum of organic pesticides, they both became interested in the problem he uncovered and proceeded to find him some specialists in the mobility of these materials in the soil and ground water environment.

They told him that trichloroethylene, also known as TCE was a volatile organic hydrocarbon used in many kinds of household and industrial chemicals, mostly as a degreaser, cleaning fluid and paint stripper. It was extremely toxic in drinking water and was suspected of causing damage to the nervous system and organs. 2,4,5-T had a long name, Trichlorophenoloxyacetic acid, and was also a hydrocarbon that was toxic to humans. It contained impurities in the form of dioxin, which Kenton knew was some pretty powerful stuff. 2,4,5-T was mainly used as a herbicide and defoliant. Both chemicals were known to cause serious contamination if introduced into the ground water. Now he needed to determine the sources for these contaminants. To do this, he first had to learn more about the various land uses and activities which could potentially contaminate the ground water beneath Jefferson City.

Things were starting to heat up again. Media inquiries about the well analyses were turned into headlines and TV news leaders all week. There was a lot of speculation about the source of the organics in the Kuma Estates wells and at one point, things became almost hysterical. Reporters were calling Kenton daily and he just didn't know what to say. It seemed like everyone was trying to blame either the local farmers and their field practices or the Kirkaldie Supply Company who handled most of the fertilizer, insecticide and pesticide sales in the Jefferson City area. In an effort to get things back into perspective the county health department, state EPA and City Managers's office of Jefferson City arranged a joint press conference to which all of the local experts, including Kenton, were invited. Unfortunately more heat than light was generated at the meeting and everyone left more frustrated than before.

* * * * * *

Suitability of Soil and Rock as Waste Depositories

Many natural soil and aquifer materials have the ability to physically and chemically filter, neutralize and breakdown waste materials resulting from mans' activities. There is the misconception, however, that all materials have an infinite capability to do this and that the ground can handle just about anything man puts into it. Perhaps this belief stems from the fact that one can't really see what happens to a substance once it enters the ground. It's just "out of sight and out of mind." This attitude may have been acceptable while there were abundant supplies of ground water and the usage was spread out geographically. With increasing densities of development and population, however, the limitations of our soil and aquifers as waste depositories and natural filtration plants are now being realized.

The natural ability of a soil or rock material to filter or absorb certain chemical constituents and contaminants from the ground water is dependent upon many factors: the surface area of the particles making up the aquifer material, the chemical conditions such as EH and pH, and the chemical characteristics of the contaminant.

Contamination Sources
Related to Land Use

A strong correlation exists between potential ground water contamination and land use. Figure 7-5 presents a table of potential ground water contaminant sources by land use category. The following is a discussion of the more prominent sources.

Septic Systems. In many regions of the United States, residential subdivisions and rural areas rely on septic systems for the treatment and disposal of wastewater. An estimated 800 billion gallons of wastewater is discharged annually to the soil by septic systems.

Of all the ground water pollution sources, septic tank systems rank among the highest for the total volume of wastewater they discharge directly to the soil and are the most frequent cause of ground water contamination. When properly designed and located these systems can be quite effective and economical. Poor maintenance and siting criteria, however, lead to the malfunction of many systems and the subsequent pollution of ground water. An estimated 40 percent of existing septic systems are not functioning properly.

The general design and concept is simple. They are made up of two parts: the septic tank and a leach field. The septic tank is designed to allow solids to settle out and to let liquid wastes flow through the tank and into a leach field made up of a series of perforated tiles. The wastewater percolates out into the surrounding soil where its various organic and chemical constituents are absorbed, filtered and chemically neutralized by the soil. It is important that the bottom of the leach field be above the seasonal high water table and that the soil zone is thick enough to allow for optimum absorption of the effluent. Figure 7-6 shows a general representation of a septic system and its relationship to ground water.

The basic design has several variations. Some of these use mechanical or pneumatic aeration methods to increase the effectiveness or capacity, or both, of the units under less than ideal natural settings.

A good soil system for receiving septic system effluent should absorb all the effluent generated and provide an optimal level of treatment before the effluent reaches the ground water. Under ideal circumstances the soil should be able to convert a pollutant into an unpolluted state at a rate equal to or greater than the rate at which effluent is added to the soil.

In many areas soil systems are not able to absorb the effluents discharged into them, either because they are not physically suitable or the systems are improperly constructed or maintained. Under these circumstances there is a high potential for nitrate, ammonia, and phosphate contamination to enter the ground water. In addition to these constituents, man made chemicals and household chemicals also frequently find their way into septic systems. Cleaning solvents such as trichloroethylene, benzene and dichloromethane are often found in septic wastewater effluent.

The greatest concern for septic system pollution is in areas where high densities of these systems exist and where the natural potential for the soil to absorb and purify effluent is being exceeded. Although most single septic system contamination is localized and can be defined as point source problems, concern is growing over the cumulative affect of non-point septic system contamination over entire regions.

Several criteria must be met before septic systems can be sited and correctly designed. Most of these criteria have to do with the leach field, the soil absorption system, and whether or not the surrounding soil or rock material is adequate to accept the wastewater. Usually local health departments and related agencies are responsible for establishing these guidelines. The soil in the leach field must be such that it meets a certain percolation rate; in other words it lets

Activity / Source	RES	COM	IND	SP	GOV	ST & E	REC	AG	MISC
1. Sanitary sewer line exfiltration	●	●	●	●	●	●	●		
2. Package treatment plants	●	●	●	●	●		●		
3. Septic tanks/leach fields	●	●	●				●	●	
4. Chemical lawn treatment	●	●	●	●	●	●	●		
5. Domestic chemical waste	●							●	
6. Above ground storage	●	●	●	●	●			●	
7. Subsurface storage	●	●	●	●	●			●	
8. Materials used in process		●	●	●				●	
9. Materials used in maintenance		●	●	●	●		●	●	
10. Loading and transporting of materials		●	●	●	●			●	
11. On-site pretreatment			●						
12. Solid waste dumps			●		●			●	
13. Solid waste landfills			●		●			●	
14. Hazardous waste disposal			●	●	●				
15. Liquid waste lagoons			●		●				
16. Extraction operations			●				●	●	
17. Junkyards		●	●					●	
18. Hospitals	●	●	●	●					
19. Cemeteries	●	●		●				●	
20. Schools	●	●		●	●			●	
21. Surface coal Storage			●		●				
22. Surface salt storage					●	●			

Activity / Source	RES	COM	IND	SP	GOV	ST & E	REC	AG	MISC
23. Subsurface petroleum storage	●	●	●	●	●			●	
24. Wastewater treatment plants			●		●			●	
25. Road salt usage	●	●	●	●	●	●	●	●	
26. Artificial aquifer recharge			●		●		●		
27. Storm sewer exfiltration	●	●	●	●	●	●	●		
28. Petroleum pipelines						●		●	
29. Spills	●	●	●	●	●	●	●	●	
30. Chemical vegetation treatment	●	●	●	●	●	●	●	●	
31. Insect control	●						●	●	
32. Deposit of materials	●	●	●	●	●	●	●	●	
33. Cropping practices								●	
34. Animal feedlots								●	
35. Sludge disposal					●			●	
36. Septage disposal								●	
37. Stormwater drainageways and basins	●	●	●	●	●	●	●	●	●
38. Stormwater drainage wells	●	●	●	●	●	●			●
39. Erosion / sedimentation	●	●	●	●	●		●	●	●
40. Excavations	●	●	●	●	●	●	●	●	●
41. Flood plains					●		●	●	●
42. Garbage deposits	●	●	●	●	●	●	●	●	●
43. Abandoned wells	●	●	●	●	●		●	●	●

Legend RES ...... Residential COM ..... Commercial IND ..... Industrial
SP .... Semi Public (Hospitals, Cemeteries, Schools)
Gov ..... Government ST&E ... Streets & Easements
REC ...... Recreational AG ..... Agricultural
MISC ..... Miscellaneous (Storm drainage ways, etc.)

From: Miami Valley Regional Planning Commission, Dayton, Ohio (1986)

Figure 7-5. ***Potential ground water contamination sources by land use category.***

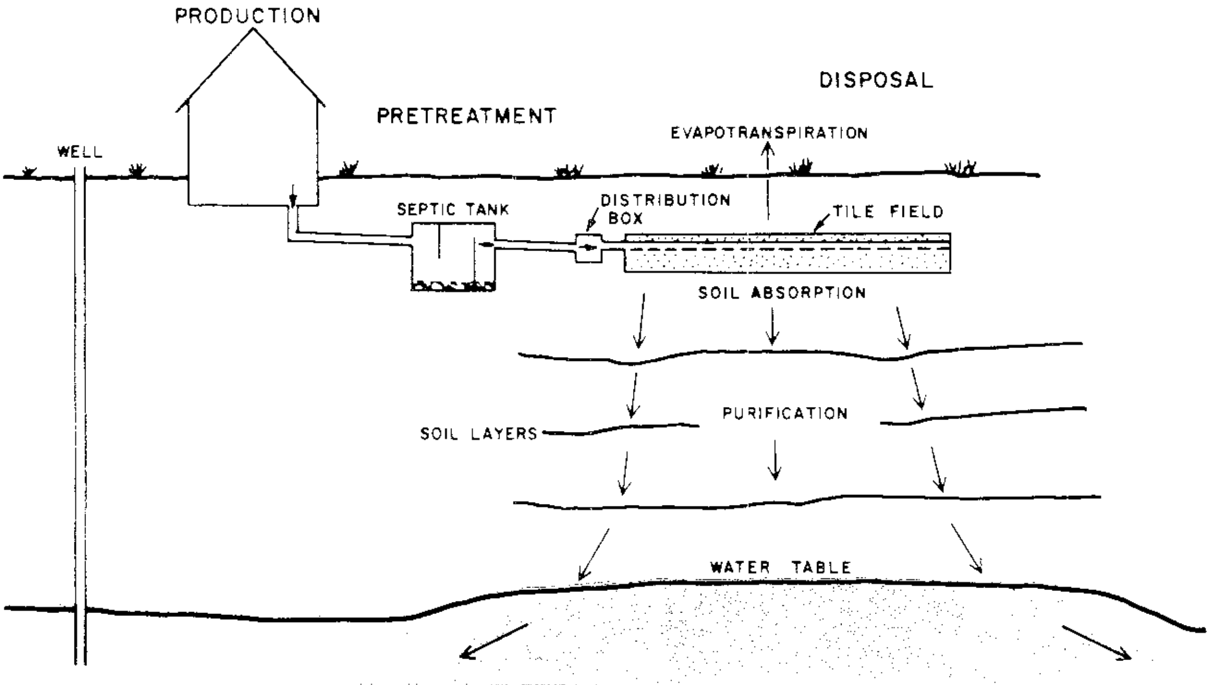


Figure 7-6. *Disposal of household wastes through a conventional septic tank-soil absorption system.*

the wastewater infiltrate through the soil at a predetermined optimum rate. Percolation tests are performed in some areas to determine this rate. Soil classification schemes are also frequently used to assess septic site suitability.

Four factors affect the performance of septic systems: leach field percolative capacity, infiltrative capacity, soil particle size, and drain field loading rate.

The percolative capacity is the rate at which effluent can be transmitted through the soil. The infiltrative capacity is the rate at which the effluent may enter the soil. The soil particle size also affects the infiltrative and percolative capacities. The loading rate is the rate of application of effluent on the leach field.

Three types of potential problems are brought on by using soils to accept septic wastes. The first one is the human health hazards associated with pathogenic bacteria and viruses in water supplies. Second is the potential for contamination of ground and surface water caused by nitrogen and phosphorus loading. Third is the possibility of increases in ground water pH that may affect terrestrial vegetation.

Nitrogen Transformation and Nitrates. The wastewater effluent that flows through a leach field includes ammonium and organic nitrogen that has small amounts of nitrite and nitrate. Usually organic nitrogen makes up about 20 percent of the total and most of this organic nitrogen is immobilized in an organic mat that develops under the leach field. This mat contains a large population of entrapped bacteria that degrade the various forms of organic nitrogen present and convert them into ammonium which is then removed by the flushing action of the effluent.

After awhile almost all of the organic nitrogen produced by the system is released as ammonium. When the effluent moves through the crust at the bottom of the leach field, almost all the nitrogen is in the ammonium form. This effluent moves down to the water table through the unsaturated zone where aerobic conditions favor the oxidation process. In sandy soils the aerobic process of nitrification is pronounced and ammonium in the effluent is converted to nitrate.

This is a necessary step in the denitrification process. Only the nitrate form will undergo the transformation to the gaseous state when the nitrate enters an anaerobic environment in the presence of denitrifying bacteria and an adequate source of organic carbon. What is important to realize here is that denitrification of nitrate is desirable and usually takes place efficiently in less well-drained soil. In very coarse soil there is a high potential for nitrification to take place and a great amount of effluent to reach the ground water as nitrate because an anaerobic environment is never encountered.

Sanitary Sewer Line Leakage. The sewer lines that connect buildings to municipal wastewater treatment plants may be damaged by tree roots, subsidence of soil and deterioration of concrete as well as other factors, which can cause breaks in the lines or misalignment of the joints. An estimated 5 percent of wastewater flow leaks out of these lines and infiltrates into the surrounding soil or ground water, or both. Sewer lines carry pathogenic organisms; high levels of nitrogen associated with human wastes; and residential, commercial, and industrial wastes including cleaners, waxes, detergents, paint thinners, household products, solvents, and other toxic chemicals.

Agricultural Activities. *Chemical Application.* Golf courses, residential lawns and gardens, recreational areas, and agricultural lands are common sites for the application of fertilizers and pesticides (herbicides, fungicides, insecticides and rodenticides). Because these chemicals are usually applied over large areas, there is significant potential for widespread non-point pollution if they percolate down into the ground water. Often the contamination potential of these materials is greatly increased in the areas where there are frequent, heavy applications, extremely permeable soils or high water tables. Areas where application equipment is filled, cleaned and where spills occur are also major sources.

With the objective of getting the most production out of a piece of land, the modern farmer has come to rely heavily on fertilizers and pesticides. These of course can be beneficial if applied at the proper times and in the correct amounts. If such care is not taken, however, these substances can cause ground water contamination. The most prominent contaminants are nitrogen and phosphates from fertilizers, followed by a long list of over 1200 different active ingredients used to formulate the 50,000 pesticide products currently on the market.

When a pesticide or fertilizer is applied to a land surface, some of the substance is used up by the plants, some is filtered out and absorbed by the soil, and some may remain unabsorbed in the the soil and be soluble with infiltrating water. When it rains, runoff water may carry these excess chemicals to surface bodies of water or the water may infiltrate through the soil zone carrying the residue to the water table.

Usually the chemical in fertilizer that causes the most problems is nitrate (NO_3). Nitrates are a health hazard in drinking water in concentrations in excess of 10 mg/liter. In the human gastrointestinal tract, nitrate is reduced to nitrite. Nitrite then enters the blood stream and reacts with hemoglobin resulting in a condition that impairs the blood's ability to carry oxygen. Nitrites are especially known to cause severe problems in infants and children under 3 years of age and young farm animals.

Fertilizers also contain ammonia and phosphate, which are mostly absorbed by the soil. Under ideal conditions, present day herbicides and pesticides are designed to be effectively filtered out by the soil and if not, they tend to degrade fairly quickly. In permeable sandy soils, however, some of these chemicals may be transported extremely rapidly to the ground water where they may reside in solution in varying concentrations, also causing contamination.

Livestock. Given enough land, any type of livestock can be raised that has no adverse effect on ground water supplies. High densities of animals in small areas, such as dairy and feedlot operations, can produce quantities of waste that exceed the carrying capacity of the soil. If correct maintenance, collection, disposal, and drainage are not provided, there can be severe impacts on surface and ground water supplies.

Manure is a high source of nitrate. Rainwater moving through a feedlot or through a heavily pastured area can transport these nitrates directly into the ground water. Disease-causing bacteria within the wastes can also be carried to the ground water supply.

Most agricultural activities do not result in ground water contamination. When they do, it is usually the result of poor farming practices in sensitive recharge areas with highly permeable soils.

Animal waste storage pits must be carefully located in settings which would reduce the chances for ground water contamination. Fractured bedrock with shallow soil cover and sandy soils above shallow aquifers are typical poor locations. These facilities should only be located after careful consideration of the geologic setting and appropriate site-specific testing.

Household Chemical Wastes

Domestic wastes are often composed of a great variety of household chemicals, some of which are hazardous alone or in combination with one another. Paints, paint removers, oven cleaners, detergents, disinfectants, automobile products, waste oil, driveway and roof coatings, and pesticides are some of the more common types of the chemicals that are used domestically and discarded. Figure 7-7 lists several of the most common household wastes that can be hazardous if not disposed of properly.

Most of these products eventually end up in municipal landfills. Here they mix with other wastes and form liquid leachates, which may percolate down into the underlying ground water. Many times these household chemicals may enter ground water through leaking sewer lines and improperly maintained septic systems.

Hazardous Waste Storage

Fuel oils, gasoline, solvents, processing and treatment products are stored either above or below ground in storage tanks. Ground water contamination from these sources may occur from spills or the improper handling of the substances in and around the tanks. A large percentage of leaking tanks leak due to ruptures, corrosion, or improperly installed fittings. Corrosion is the most frequent cause of leaks in underground gasoline storage tanks. The age of the tank is usually the critical factor. Spillage from transfer of these materials is a common problem. Careless handling over time can result in significant contamination of the soil and ground water.

Solid Waste Dumps

A dump is an area where there is an indiscriminate, unauthorized, and unsupervised deposition of any type of waste. Many of these dumps are open with no provision for covering the waste material. Even though dumps are usually illegal, they still continue to cause a potential threat to ground water resources. They are often located in manmade or natural depressions such as gravel pits and quarries, which are geologically unsuitable for disposal because of their high permeability or high water tables, or both. Although originally intended just to receive demolition debris, a lack of supervision and monitoring allows for other types of materials to be disposed.

Chemical	Health Hazards	Consumer Products
Benzenes	Carcinogen	Spot removers, gasoline
Carbon tetrachloride	Suspected carcinogen liver and kidney damage	Paint/varnish remover, liquid degreasers,spot removers, old fire extinguishers
Chlorobenzenes	Irritant; possible liver and kidney damage	Deodorizers, dyes, metal polish, moth repellent, disinfectants
Chloroform	CNS depression, liver and kidney damage	Cough medicine, linaments
Methylene chloride (dichloromethane)	Respiratory irritant, CNS depression, alters ability of blood to carry oxygen to body tissue	Paint removers, degreasers, refrigerants
M-xylene	Possible reproductive hazard, liver and kidney damage	Spray paint,paint removers, degreasers, gasoline
Napthalene	Liver damage, blood disorders	Bathroom deodorant, insecticides, moth repellent, rug cleaners
O-phenylphenol	CNS depression, irritant	Disinfectants, preservatives
Pentachlorophenol	Toxic to liver, kidney, and CNS. Contains hexachlorobenzene, which is carcinogenic in rats and mice. May contain dioxin.	Wood preservatives
Phenol	May cause severe burns upon skin contact, CNS depression	Disinfectants, deodorants, furniture polish
Tetrachloroethylene (PERC)	Suspected carcinogen and mutagen; liver and blood damage	Stain remover, paint stripper, contact cement, degreasers, wax removers, shoe polish, pesticides, rug cleaner
Toluene	Possible reproductive hazard, liver and kidney damage	Spray paint, thinners, glue, cosmetics, gasoline
Trichloroethylene	Suspected carcinogen, central nervous system (CNS) and organ damage	Cleaning fluid, strippers, and upholstery cleaner
2,4,5-T	Suspected animal carcinogen. May contain dioxin.	Pesticides

Figure 7-7. ***Chemicals, products, and health effects of some household hazardous wastes.***

Solid Waste Landfills

Municipal landfills accept waste from residential, commercial, or industrial sources. Most are sanitary landfills where the waste materials are covered daily with a layer of soil to reduce the nuisance problem or odor, pests, and combustion. The wastes may be in solid, semi-solid, liquid, or in containerized gaseous form. Although most sanitary landfills are only intended to receive non-hazardous wastes, some portion of most of the waste is likely to be hazardous. The combination of non-hazardous wastes in landfills often results in the formation of hazardous leachates that if not properly captured and contained can percolate down into the ground water zone. Figure 7-8 lists the most common leachate characteristics from municipal solid wastes.

Many large industries and government installations operate their own solid waste landfills as a more economical alternative to the transport of these wastes to other distant sites. These facilities are usually privately monitored which may result in their being used as depositories for inappropriate materials. Figure 7-9 lists some of the more common components in industrial waste.

Another problem is the existence of older landfills that were established before regulation or enforcement existed.

To minimize the amount of contamination from landfills, criteria regarding siting, design, construction, operation and maintenance must be met. Figure 7-10 lists some of these criteria for siting of sanitary landfills in Illinois.

In past decades, many landfills were located in areas of low relief which were easily filled in once wastes were deposited. Features such as sinkholes, quarries and gravel pits, which serve as natural conduits to the aquifer systems below, were frequently used for the disposal of wastes. Beneath these wastes, liquid leachates accumulate which then move downward transported by infiltrating water. It may take many years or even decades for the leachates to accumulate and make this journey, which means that many problems have yet to be detected.

No natural earth materials are impervious to water. As a matter of fact, there are none that won't leak given enough time.

Rainwater percolating through the waste, the amount of moisture in the wastes, and fluctuating ground water tables all contribute to the formation and transport of hazardous leachates. Leachates may continue to be produced by old landfills for many decades after the waste disposal has ceased. Locating the sites of abandoned landfills is another formidable problem encountered in attempting to remedy degraded aquifer areas.

In the past few years, the use of natural clay liners beneath landfills to stop the downward migration of leachates has gained some acceptance. This, however, is not a permanent solution because no natural materials are impermeable. All landfills will eventually leak. If they didn't leak, in humid climates they would eventually fill up with water and overflow, which of course does not happen. The water must be going somewhere which means it is finding its way out through less impermeable zones, carrying with it the concentrated leachates. It all becomes a question of how long is an acceptable amount of time to not have to deal with the problem.

This is not to say that all landfills are definite problems. A well-engineered landfill should include methods of reducing the flow of water through the waste material. This is often done by capping the landfill or by grading the surface to increase runoff. Siting of landfills should avoid the presence of springs and the underlying geology that may allow the leachate to reach ground water quickly. Leachate collection and treatment networks are highly desirable.

Others (Heath and Lehr, 1987) believe that even more stringent practices should be observed. They think that we should try to reach two goals in considering the future selection and construction of waste-disposal sites:

1. Minimum possible pollution of ground water, regardless of whether it is presently the source of public, domestic, or industrial supplies.

2. Minimum possible pollution of surface water where the pollution could have an immediate and adverse effect on public water supplies, fisheries or wildlife resources.

Components	Median value (ppm)[a]	Ranges of all values (ppm)[a]
Alkalinity ($CaCO_3$)	3,050	0 — 20,850
Biochemical Oxygen Demand (5 days)	5,700	81 — 33,360
Calcium (Ca)	438	60 — 7,200
Chemical Oxygen Demand (COD)	8,100	40 — 89,520
Copper (Cu)	0.5	0 — 9.9
Chloride (Cl)	700	4.7 — 2,500
Hardness ($CaCO_3$)	2,750	0 — 22,800
Iron, Total (Fe)	94	0 — 2,820
Lead (Pb)	0.75	<0.1 — 2.0
Magnesium (Mg)	230	17 — 15,600
Manganese (Mn)	0.22	0.06 — 125
Nitrogen (NH_3)	218	0 — 1,106
Potassium (K)	371	28 — 3,770
Sodium (Na)	767	0 — 7,700
Sulfate (SO_4)	47	1 — 1,558
Total Dissolved Solids (TDS)	8,955	584 — 44,900
Total Suspended Solids (TSS)	220	10 — 26,500
Total Phosphate (PO_4)	10.1	0 — 130
Zinc (Zn)	3.5	0 — 370
pH	5.8	3.7 — 8.5

a) Where applicable.

Figure 7-8. ***Summary of leachate characteristics based on 20 samples from municipal solid wastes. (Source: U.S. EPA, 1977).***

	Metals mining	Primary metals	Pharmaceuticals	Batteries	Inorganic chemicals	Organic chemicals	Pesticides	Explosives	Paints	Petroleum refining	Electroplating
Ammonium salts		X								X	
Antimony	X				X				X		
Arsenic	X	X	X		X					X	
Asbestos					X				X		
Barium									X		
Beryllium	X									X	
Biological waste			X								
Cadmium	X	X		X	X				X	X	X
Chlor. hydrocarbons					X	X			X		X
Chromium		X	X	X	X				X	X	X
Cobalt									X	X	
Copper	X	X	X	X					X	X	X
Cyanide		X			X					X	X
Ethanol waste, aqueous			X								
Explosives (TNT)								X			
Flammable solvents						X			X		
Fluoride		X			X						
Halogenated solvents			X								
Lead solvents	X	X		X	X				X	X	X
Magnesium	X										
Manganese		X									
Mercury		X	X	X	X				X	X	
Molybdenum										X	
Nickel		X		X	X					X	
Oil		X								X	X
Organics, misc.						X					
Pesticides (organo-phosphates)							X				
Phenol		X								X	X
Phosphorus					X						X
Radium	X										
Selenium	X	X	X							X	
Silver				X						X	X
Vanadium										X	
Zinc	X	X	X	X	X				X	X	X

Source: U.S. EPA, 1977.

Figure 7-9. ***Components of industrial waste. (Source: U.S. EPA, 1977).***

1. **Type of unconsolidated material**
   Favorable: glacial till, lake silts and clays, windblown silt (loess)
   Unfavorable: sand, gravel
2. **Thickness of unconsolidated material**
   Favorable: 50 feet or more (30 feet if no trenching is proposed)
   Unfavorable: less than 50 feet (30 feet if no trenching is proposed)
3. **Type of bedrock**
   Favorable: shale
   Unfavorable: sandstone, fissured limestone, or dolomite
4. **Local sources and potential sources of water**
   Favorable: deep bedrock wells; sand and gravel wells with logs showing thick impermeable cover over aquifer; dug wells if 500 feet or more from the site
   Unfavorable: shallow bedrock wells (particularly in fissured limestone), sand and gravel wells with logs showing thin cover over aquifer
5. **Site topography**
   Favorable: flat upland areas; heads of gullies and ravines; dry strip mines
   Unfavorable (require operational engineering): depressions where water accumulates, lower reaches of gullies, stream floodplains, other sites near surface water areas where leachate might discharge into the water

If 1, 2, 4 and 5, or 1, 3, 4, and 5 are favorable, there is little possibility that ground water contamination will occur.

Source: R. Berg *et al.*, *Potential for Contamination of Shallow Aquifers in Illinois* (Ill. State Geological Survey, March 1983).

Figure 7-10. *Criteria for evaluating sanitary landfill sites in Illinois.*

Elimination of ground water pollution is extremely expensive and requires a long period. With ever-increasing populations and water needs, we must anticipate that ground water will be fully exploited. Pollution of any surface water source can be eliminated usually in much shorter time spans than ground water pollution.

Hazardous Waste Disposal

The USEPA has defined hazardous wastes as any flammable, corrosive, explosive, or toxic waste that may cause or contribute to serious illness or death or that may pose a substantial threat to human health or the environment when improperly managed.

Hazardous waste landfills licensed after January 1983 are required to have containment liners and leachate collection and removal systems. Natural clay liners or synthetic plastic liners are acceptable, although both types of liners have been known to deteriorate and leak because of contact with various chemicals. Even the use of both kinds of liners (double lining) may not be sufficient security under certain conditions. As with landfills, older hazardous waste disposal sites that have been exempted from regulations will pose significant potential threats to ground water resources in the future.

Liquid Waste Lagoons

Sometimes municipalities and industries use ponds or lagoons for storing and treating residuals from drinking water treatment and wastewater treatment plants or industrial wastewater. Agricultural waste ponds are among the most serious sources of contamination in rural areas. Manure ponds from feedlots or dairy herds are examples of this problem.

You must realize that in all the categories of contaminant sources listed above, their greatest potential lies in their location in proximity to public drinking water sources. There are many other sources of contamination including extraction operations in quarries and gravel pits, junk yards, automobile wrecking yards, hospitals, cemeteries, schools, surface storage of coal, subsurface petroleum storage, wastewater treatment plants, road salt usage and storage areas, artificial recharge impoundments (impoundments which are actually excavated and used for the purpose for recharging an aquifer), storm sewers, cross-country oil and gas pipe lines, transport route spills, animal feedlots, sludge disposal, erosion, floodplains, storm water drainage pits (dry wells), abandoned wells, injection wells and drainage ditches and tiles.

VIII. Ground Water Monitoring and Sampling

It was the middle of August now and with all the publicity over possible ground water contamination in Jefferson City some of the larger businesses and industries had gotten a little uneasy. A few had actually initiated their own monitoring programs. The usual reason for doing so was "to assure the safety of the citizens of Jefferson City." Of course it couldn't hurt to have your own data if by chance your company got hauled into court! Various state and federal agencies were also beefing up their data collection programs.

This created a lot of work for the handful of well drillers and contractors who were being called on to install all kinds of monitoring wells and test borings. It was fairly routine for Kenton to pass by one or two of these drilling operations everyday.

On the southeastern side of town, the USEPA was having some additional monitoring wells installed down-gradient from the Erinakis Scrap Lead Site. Out at the Kuma County Incinerator and Landfill a couple of different groups were doing the same. On that property the County had contracted for an entire monitoring well network to be installed consisting of four or five separate clusters of three wells, each well screened at a different level. Surrounding that property a concerned group of Jefferson City residents, calling themselves the Citizens Against Resource Pollution (CARP), had arranged for the geology department at the state university to install some monitoring wells and start a data collection program. The Jefferson City Water Department was also installing monitoring wells, and initiating and upgrading its data collection efforts around the municipal well fields along the river. Yes, there was a great deal of activity in Jefferson City this summer. One man told Kenton that if the drilling kept up, the place would look like a prairie dog town.

On a couple of occasions, Kenton stopped and watched the crews work. During those visits he learned a lot about drilling and got acquainted with two different drillers: Daryl Curley of Hydronamics, Inc. and Stanley Fiori of Fiori Water Wells. Kenton couldn't get over the difference between these two characters and their approaches to the same task.

Curley, a tall slender, middle-aged fellow with a handlebar moustache, thought of himself as the epitome of the modern driller. As a matter of fact, he didn't even call himself a driller. He would always sign his drill logs "Daryl Curley, Aquifer Penetration Engineer." He was a know-it-all and slightly obnoxious, but Kenton enjoyed hearing him talk about his "modern approach" as compared to the "oldtimers." Knowing Curley, watching him work and hearing about his past work from other folks, had convinced Kenton of one thing: it takes more than a fancy rotary rig and a blue jumpsuit with a company logo on the pocket to be a good well driller. Sure, some of the good ones have all of that, but they also have patience, an uncanny eye for detail and know what their rig is telling them. This guy was all glitter and Kenton just wasn't sure of the integrity of his work. He seemed to work too fast, overlook too many details and cut corners whenever he could.

Then there was Stanley Fiori, 64, about five-foot-five, thick bushy eyebrows, fingers all gnarled up from arthritis and forearms as big around as the augers he tossed around. And very quiet—Curley uttered more words in 10 seconds than Stanley Fiori did in an entire day. Kenton watched him for a couple hours one day and couldn't get over the patience that Fiori had with the old cable tool drill rig he had inherited from his father. Watching Fiori and his two man crew work was a little like watching a ballet or a skating exhibition. Each had a particular task and was always ready to perform it with the right tool at the right time. Every movement was coordinated with another, so that the entire drilling process was a string of fluid motions. Kenton used to joke that well drilling was one of Jefferson City's highest art forms.

Fiori wasn't a scholar, but he managed to write down every single detail about each sample and foot of earth that came out of a borehole. No, he couldn't put in as many production or monitoring wells as Curley, but the ones he did manage to install would yield the drinking water or accurate samples needed.

Kenton learned that just like in everything else, there were good and bad well drillers and you shouldn't judge them on how they looked. You had to watch them work.

Meanwhile, back at the ranch houses. . . . The folks at Kuma Estates with the organics in their wells didn't have many options to provide alternative water supplies. Very likely new wells would have the same problem. A petition to the City might bring in a water line from the municipal system, but in addition to the expense of laying the line, which they would very likely have to bear, it might take a year or more for the gears of government to grind through the process even if they considered it an emergency. To the residents with the bad wells it certainly was an emergency and almost all of them had gone to bottled water just as soon as they were notified by the county health department.

* * * * * *

Contamination Detection

Ground water monitoring techniques will vary according to the type of contamination and the hydrogeologic conditions. Every monitoring venture must be accompanied by a well thought out plan, which can usually be supplied by a competent technical consultant. First you must define the objectives of the program: what is to be monitored and what are the boundaries of the study area. Next, the geographic conditions must be considered. The source of contamination must be determined as accurately as possible as well as its proximity to areas of ground water production. Climate and topographic conditions must be studied. Finally, the hydrogeology of the area and the various physical and chemical processes acting on the contaminant must be understood.

Monitoring Wells

The primary objective of designing and constructing monitoring wells is to obtain representative information and samples of the ground water at a specific point. There are two categories of monitoring wells: those designed to measure water levels only and those designed to collect water samples. The design and construction of monitoring wells is dependent upon the types of measurements and types of samples being collected.

Construction

Drilling the holes into which monitoring wells are installed is done many ways. Each method has its own advantages and disadvantages depending upon the geology, time, and money available and the ultimate purpose of the well. Figure 8-1 summarizes different drilling methods as explained in detail in *Ground Water and Wells*, by Fletcher Driscoll.

Most monitoring well casing diameters are between 2 and 4 inches. Small casings are more favorable because they are less expensive, may be purged faster to obtain representative samples and several can be nested in a single borehole, which means less drilling.

Figure 8-2 shows three monitoring wells clustered in a single hole. Each well is screened at a different level for the detection of contaminants with different densities. The construction is fairly typical for most monitoring wells, either single or nested. An impermeable bentonite seal is usually positioned above and below the well screen or perforations so that water from outside the level of sampling does not enter the casing. A bentonite seal is also placed at the top of the boring to prevent the infiltration of surface water down along the casing. A sand or gravel pack is backfilled around the casing to increase hydraulic conductivity around the well and allow ground water to permeate freely into the area around the well screen. The slot size of the well screen is an important consideration. The size must be correctly chosen so the sediment and sand or gravel pack around the well cannot enter the casing and fill in the bottom of the well.

Several factors are considered in determining the depth to which the well will be drilled: the level at which information is being collected, seasonal fluctuations in water levels, and contaminant densities.

Casing material is extremely important and depends upon the types of substances being collected. The well casing must not react with the chemicals in the ground water or the results of chemical analysis may be thrown off and the entire monitoring program invalidated. Figure 8-3 summarizes various casing materials.

Placement. To detect a contamination plume, a minimum of three monitoring wells is needed. They should be arranged in a triangular arrangement so that one monitoring well is on the up-gradient side of the contamination source and two wells arranged on the down-gradient side parallel to the source of contamination. Both the width and the vertical dimension of a contaminant plume must be determined. And once detected, it may be necessary to extend the monitoring network to improve resolution. Figure 8-4 shows this type of monitoring network pattern around a landfill.

Method	Consolidated Material	Unconsolidated Material	Maximum Depth (ft)	Hole Diameter (in)	Yield (gpm)	Advantages	Disadvantages
Cable tool	●	●	2000	4-24	3-3000	Good samples Good drilling data Operates in all formations	Lengthy process Expensive
Hydraulic rotary	●	●	any	3-18	3-3000	Hard and soft formations Readily available Drill at any depth Casing not required Reliable sample Inexpensive	Drilling fluids difficult to remove Shouldn't use with bentonite if metals are present Interferes with organic sampling Limited drilling data Circulates contaminants
Reverse circulation		●	200	16-48	500-4000	Quick Good geologic data Formation water is not changed	Requires large volumes of water Limited hydrologic data Expensive
Air rotary	●		any	12-20	500-3000	No drilling fluid No contamination Hard rock formations Good hydrologic data Readily available	Casing is required Caving results in soft formations Mixing
Jetting		●	50	1.5-3	3-30	Quick Inexpensive Easily transported	Sample contamination Can't seal Limited to small diameters Large quantities of water Limited to soft formations Limited to shallow depths
Solid stem continuous flight auger		●	75	6-36	3-100	Mobile Quick Inexpensive No drilling fluid Minimal contamination	Cannot use in hard rock Limited to shallow depths Subject to borehole collapse Limited hydrologic data
Hollow stem continuous flight auger		●	75	6-36	3-100	Mobile Quick Inexpensive No drilling fluid Minimal contamination Can use natural gamma-ray logging in borehole Can use grout sealing	Cannot use in hard rock Limited to shallow depths Samples subject to contamination Limited hydrologic data
Bucket auger		●	35	2-8	3-50	No drilling water is required Easy Excellent formation sampling	Soft formation only Shallow depths Rigs aren't widely available

Figure 8-1. ***Summary of drilling methods and applications.***

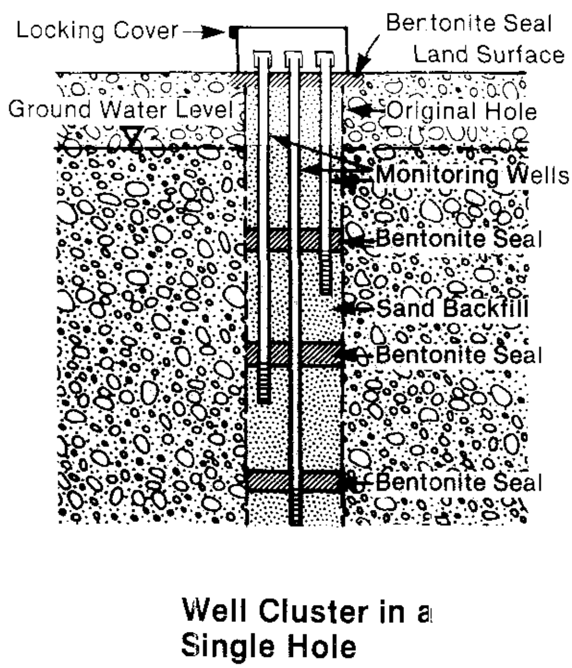


Figure 8-2. *Construction of monitoring well cluster.*

Types	Advantages	Disadvantages
PVC (Polyvinylchloride)	Chemically resistant to weak alkalies and strong mineral acids Lightweight Low priced	Less durable and more temperature sensitive than metallic materials May absorb or leach some chemicals Low chemical resistance to Ketones, esters and aromatic hydrocarbons
Polypropylene	Chemically resistant to mineral acids, oils, alkalies, alcohols, keytones, and esters Lightweight Low priced	Less durable and more temperatures sensitive than metallic materials May leach constituents into groundwater Cannot be slotted easily
Teflon	Excellent chemical resistance Lightweight High impact strength	Wears easily and has low tensile strength Expensive Not readily available
Kynar	Wears slower than Teflon and has greater strength than Teflon Excellent chemical resistance Lower priced than Teflon	Not readily available
Mild Steel	Durable, not temperature sensitive Readily available Low price	Chemical resistance not as great as stainless steel Heavy May leach constituents into groundwater
Stainless Steel	Durable, not temperature sensitive Resistant to oxidation and corrosion Readily available Moderate price	Can act as a catalyst in organic reactions Heavy May leach chromium in highly acidic waters

Figure 8-3. *Advantages and disadavantages of well casing materials.*

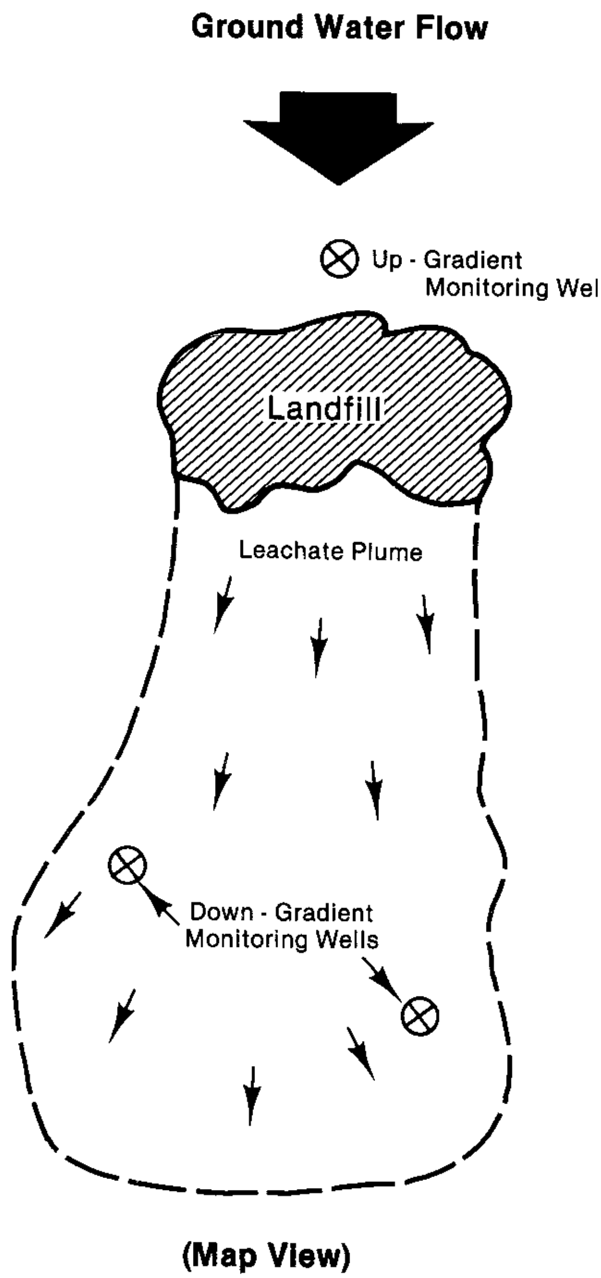


Figure 8-4. *Triangulation method for ground water monitoring.*

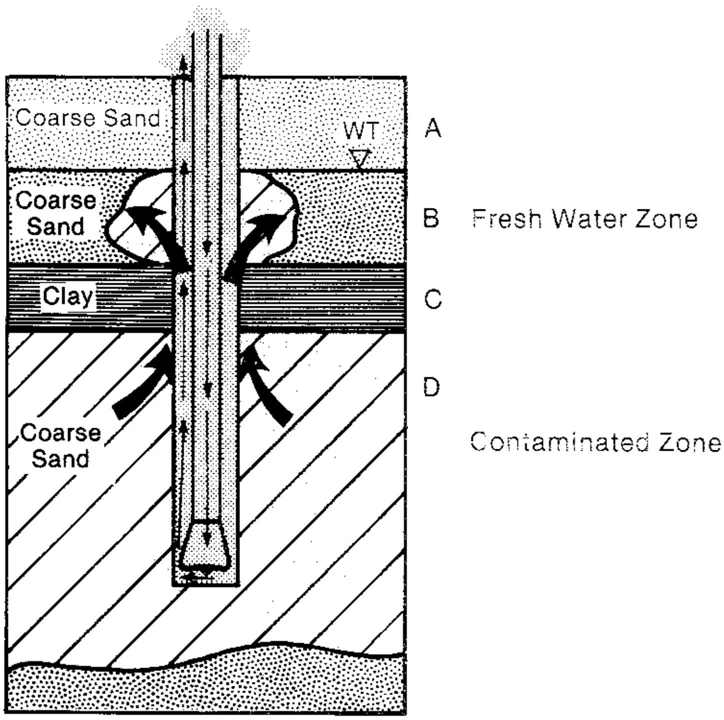


Figure 8-5. *Mixing of constituents from different zones while drilling.*

IRIS

Understanding the basic spatial relationships of the subsurface geology is of great advantage. Knowing the presence of highly permeable or impermeable layers can aid in the positioning of well screens. Remember the ground water carrying the contaminants will flow first along paths of high conductivity. Being aware of zones that may separate contaminated water above from uncontaminated water below can also pay off. Care can be taken to avoid drilling through these zones or precautions can be taken to pack off these zones during drilling. Failure to do so could result in the mixing of contaminants between zones as shown in Figure 8-5.

Sample Collection

A great deal of time and money can be spent on installing monitoring wells, and it can all be wasted if the proper sampling techniques are not used. Sampling must be carried out by someone, a consulting hydrogeologist or laboratory field technician, using standardized sampling methods.

Sampling schedules should be adjusted according to the rate of contaminant or ground water movement. The higher the hydraulic conductivity, the more often the water should be sampled.

In sampling procedures, one must obtain a volume of water that is representative of the water in the surrounding formation. This usually means that the well casing must be evacuated before sampling can begin.

Sampling and pumping activities can cause physical and chemical disturbances in and around the well. Great care should therefore be taken not to disrupt the natural system. The use of certain pumps can cause turbulence that results in oxidation of samples. Oxidation of organics, sulfides, iron, ammonium and other metals, can remove or alter the targeted constituents in solution.

The material used in the construction of the pump or sampling device can sometimes contaminate the sample. If sampling equipment is not dedicated to a single well, it must be properly cleaned and decontaminated before being used at another site. Technological advances in sampling equipment construction and design allow personnel to match the appropriate equipment to the type of sampling being done.

Finally, once the sample is obtained, it must be properly labeled, preserved, and, within a reasonable amount of time, submitted for analysis. Many samples deteriorate from exposure to sunlight, temperature, oxygen, and turbulence and, therefore, such refrigerated, enclosed protection as ice chests must be provided to preserve the samples.

Well Abandonment

Test holes, borings, test wells, monitoring wells, piezometers, or production wells, if they are not to remain as permanent facilities, must be properly secured for abandonment. In all cases, that means filling the well bore with a bentonite or other clay slurry, cement grout or other approved sealing material. Casing, if it is to be removed, should be pulled after the sealing mixture is added. There are approved methods for plugging all kinds of wells which are described in standard references. Many states have specific regulations for abandonment which must be followed. Improperly sealed or unsealed wells are the frequent cause of surface contamination entry into the ground water regime.

IX. Ground Water Management

Now even though Kenton knew what the contaminants were that had shown up in some wells out in Kuma Estates, he still didn't know their exact source or sources. From their description of use, they could be found just about anywhere—in private households, machine shops, farms, garages and any number of other commercial and industrial establishments. He went through the Yellow Pages circling some of the possibilities. There were so many potentially contaminating activities in Jefferson City—the list seemed endless. And as far as he knew there was no organized plan to deal with such problems before they occurred or even after they occurred. The region definitely needed some sort of coordinated management program. He knew that several agencies, such as the state EPA, the Soil and Water Conservation District, Regional Planning Agency, etc., ought to be notified. He was also aware that in some states, such as Rhode Island, there was a Resource Conservation and Development Project Coordinator who could be of great help. Somehow he felt he still didn't have enough concrete information to get them involved, but he made a note to start that process as soon as possible.

* * * * * *

In its most basic sense, management entails the manipulation or control of a system. By controlling one or more elements or variables of that system, the inflow and outflow relationships can be influenced. Ground water systems readily lend themselves to management.

Whether the system be a single aquifer or multiple aquifers, direct and indirect factors can be controlled to bring about a certain response from the system. The list of possible management practices is quite long. For example, in areas where water quantity might be a problem, activities can be conducted that may enhance the infiltration capacity of the primary recharge area. Catchment basins, impoundments and channels are sometimes used to collect and spread surface water out over an area to increase potential infiltration. In highly developed areas, permeable pavement that allows precipitation to pass through directly into the soil rather than running off can be used in roads and parking lots.

With the growing concern over ground water in the United States, there has been an increase in the number and types of programs aimed at ground water protection and management. Some of these programs are locally based, and others, designed to protect regional aquifer systems, encompass large metropolitan areas. Regional programs are now being developed and implemented in Long Island, New York; Dade and Broward Counties, Florida; Cape Cod, Massachusetts; Spokane County, Washington; and Dayton, Ohio — to name a few. Many states are devising their own aquifer protection and management strategies. Federal programs now mandate wellhead protection programs for most ground water-based public drinking water supply sources. Figure 9-1 lists the status of ground water protection strategies by state.

Management Strategies

Depending on the social, economic, political and geologic settings, there are four basic management strategies utilized to address ground water problems: voluntary, passive, active, and interactive.

Aquifer protection and ground water management programs frequently start out as voluntary efforts. Usually several different jurisdictions are involved, each having its own authority over a specific area.

When an aquifer or aquifer system underlies an area divided into several different political jurisdictions, protection and management actions are effective only if all the jurisdictions take an active role. There are cases where the recharge area of an aquifer does not lie over the aquifer, but rather many miles away. An effective management program must protect not only the aquifer reservoir, but also the distant recharge area. If these areas underlie different political jurisdictions, a cooperative effort is required.

Cooperative voluntary management strategies are among the easiest to initiate. Yet they are the least enduring because changing economic and social factors often threaten the cohesiveness of the participating communities.

Passive strategies involve aquifer protection controls and measures embedded in the governmental infrastructure of a community or region. Zoning or land use regulations are examples, and more specifically, building codes, subdivision ordinances, reduced dwelling density regulations and regulations on the storage of hazardous wastes, fuels and raw materials. The main disadvantage of zoning controls is that in highly developed areas, pre-existing activities often can't

	Specific State Statutes for Groundwater	Existing Policy for Protecting Groundwater Quality	Policy Under Development	Nondegradation	Limited Degradation	Differential Protection
Alabama			■			
Alaska						
Arizona	■	■			■	■
Arkansas			■			
California		■	■	■		
Colorado			■	■		■
Connecticut		■				■
Delaware		■	■			
Florida	■	■			■	■
Georgia	■	■		■		
Hawaii		■	■			
Idaho		■		■	■	■
Illinois			■			■
Indiana			■			
Iowa			■	■		
Kansas	■	■				
Kentucky			■			
Louisiana						
Maine	■	■	■	■		
Maryland					■	■
Massachusetts		■				■
Michigan		■	■	■		
Minnesota		■	■	■	■	
Mississippi			■			
Missouri			■	■		
Montana		■		■		
Nebraska			■			
Nevada		■		■	■	
New Hampshire		■		■		
New Jersey	■	■	■	■	■	
New Mexico	■	■			■	
New York	■	■			■	
North Carolina		■				■
North Dakota			■			
Ohio			■			
Oklahoma	■	■				
Oregon		■			■	
Pennsylvania			■		■	
Puerto Rico						
Rhode Island			■	■		
South Carolina			■	■	■	
South Dakota			■			
Tennessee			■			
Texas						
Utah		■	■			
Vermont		■			■	■
Virgin Islands			■		■	
Virginia	■					
Washington		■	■	■	■	■
West Virginia			■			
Wisconsin	■	■			■	
Wyoming	■	■			■	■
Total	12	27	28	16	17	12

Source: U.S. EPA, Office of Ground-Water Protection, *Overview of State Ground-Water Program Summaries, Vol. 1* (Washington, D.C.: March 1985), Tables A-6 and A-7.

Figure 9-1. State ground water protection strategies.

be zoned out because of "grandfather clauses." Zoning must be looked at as a long term process where restrictions are gradually tightened to eventually rid an area of potentially contaminating activities.

Active strategies entail actual monitoring of the ground water resource. Usually one or two variables such as evaporation or precipitation are monitored and water resource usage adjusted on the basis of information gathered. For example, a community involved in an active strategy may, after a prolonged drought, reduce or cutback on the production of ground water supplies for public consumption. Seasonal precipitation data, in this case, is used as an indicator of the amount of relative recharge to the aquifer. When precipitation drops below a certain level for the season, production is reduced accordingly. This strategy is based upon a non-immediate feedback.

A strategy dealing with more immediate feedback, usually on a daily basis, is an interactive strategy. Here the emphasis is the monitoring of two or more variables, such as certain chemical concentrations in the ground water or the measurement of salinity or conductivity, that directly relate to the ground water resource.

Two approaches to the basic ideas behind strategies to reduce contamination of ground water have been alluded to earlier. We might refer to these as the "delay and decay" school of thought and the "dilute and disperse" approach. The first of these uses the idea of sorption of contaminants close to their source until they can naturally decay or be reacted with other constituents in the aqueous environment. The objective of the second is to disperse the contaminants and thereby reduce their concentration. Because each requires a different kind of environment, for example fine grained, low hydraulic conductivity, low gradient versus high flow, high recharge conditions, each is suitable only under the appropriate conditions. Because the immediate geologic environment of proposed waste disposal or other sites are not easily modified, careful attention must be paid to evaluating a setting prior to plan implementation.

In coastal areas where saltwater intrusion may be a problem, certain types of instruments can be installed on wells to continually measure salinity. When salinity rises to a certain threshold level, a sensor triggers a cutback in production at the well to prevent the upconing of saltwater into the freshwater aquifer zone. This type of feedback is immediate and direct and offers the most control over the resource usage.

Protection, Remediation and Controlled Degradation

In a ground water management program, there are three basic approaches to protection and management: aquifer source protection, remediation, and controlled degradation.

In aquifer source protection there are two basic approaches. The first is sensitive area protection. This approach focuses protection measures and actions on areas that are directly connected with the aquifer, especially recharge areas where precipitation actually infiltrates and enters the ground water zone.

The second approach to aquifer protection is contaminant source control. In this approach, preventative measures are directed toward potential and existing contaminant sources such as waste lagoons, septic tanks, fuel storage tanks, and landfills. A common example is the implementation of regulations restricting the storage of specific chemicals. Contaminant source controls can also be targeted on land use above an aquifer.

Management of specific areas may also be approached from the standpoint of remediation. When a ground water resource actually becomes contaminated, the time to use preventative measures has passed and the only effective approach left is remediation.

Two basic categories of remedial action are: treatment and restoration. Most communities today must perform some type of treatment on ground water supplies. In the past, this treatment was usually to remove mineral constituents, and organic constituents which limited the esthetic quality of the water. More and more, however, ground water is being treated for such potentially harmful chemical compounds as synthetic organic chemicals, hydrocarbons, pesticides, and pathogenic bacteria. These treatments involve a great deal of technology and incur long-term operating and maintenance costs.

Frequently in highly developed areas, the ground water has sustained some level of degradation. If developing alternative supplies is not feasible, then the available ground water supply must be extracted and treated. Rehabilitative treatment may involve the use of activated carbon adsorption, air-stripping systems or biochemical methods. Some of the advantages and disadvantages of remedial methods are presented in figure 9-2.

			Advantages	Disadvantages
Aquifer Rehabilitation	Withdrawal Treatment and Reinjection		• Perhaps the most widely practiced method for controlling contaminated groundwater	• Expensive • Requires ongoing maintenance and operational costs • No guarantee that entire plume will be intercepted
	In Situ Treatment	Chemical	• Capable of eliminating, immobilizing or precipitating certain chemical species from groundwater	• No guarantee that complete mixing of treating agents occurs • It is hard to estimate just how much of the chemical reagent or biological agent is needed • May be expensive • May cause an adverse impact on the aquifer
		Biological	• Successfully removes petroleum products as well as other organics from groundwater	
Withdrawal Treatment and Use			• Perhaps the most cost effective method	• There may be problems associated with treatment methods of aeration and adsorption

Figure 9-2. *Summary of advantages and disadvantages of remedial methods for aquifer rehabilitation and withdrawal, treatment and use.*

The second type of remedial action involves restoration, an attempt to return the ground water resource to its original condition. Restoration is sometimes attempted in highly developed areas in drastic situations of acute local contamination. Cleaning up hazardous waste dumps, landfills, ponds, pits, and lagoons would be restoration projects. The clean up may involve completely removing soil or aquifer materials from a site, the "hot spot." In some cases, the water may be pumped from the ground, treated, and reinjected into the aquifer.

Passive physical constraints such as caps on landfills or subsurface containment walls and barriers can be used to alter the ground water flow paths and prevent further contamination. Interlocking steel sheet piles are sometimes driven through the aquifer into underlying impermeable strata to create a barrier. In other cases a cement mixture called grout is injected into closely spaced holes drilled into the subsurface. The grout will spread out through the formation and interfinger with grout from adjacent holes. The resulting barrier is called a grout curtain. Sometimes a trench may be excavated around a site and filled with a bentonite slurry mixture. This is called a slurry trench cutoff wall and is a relatively effective barrier to ground water flow. In some cases continual pumping or injection of ground water may be used to hydrodynamically control the hydraulic gradient to divert contaminated water from production wells. Figure 9-3 presents some of the advantages and disadvantages of these physical containment techniques.

The final management approach is controlled degradation. In certain highly developed metropolitan and industrialized regions, social, economic, and political conditions exist that may not permit the effective implementation of protective or remedial measures. There is often a "growth at all costs" attitude or a lack of interest or commitment in the community. In some areas where many jobs are provided by the industry contributing to the degradation of the ground water resource, the community may feel it must choose between jobs or clean up. So to keep jobs, a certain amount of degradation of the ground water is tolerated.

Restoration procedures can take years or decades and cost many millions of dollars. Implementing aquifer source protection measures before problems occur is definitely more economical in the long run.

Yet, to implement ground water management programs effectively, every individual who has any direct or indirect connection to the resource must be involved—and that includes everyone. In areas where programs are being developed or are underway, individuals may be involved on a voluntary or involuntary basis. In either case, success depends upon the motivation of individuals to participate. The motivation needed to fuel effective management programs may be supplied by a variety of mechanisms: educational, operational, economic or regulatory. Figure 9-4 shows a motivational spectrum of management mechanisms.

* * * * * *

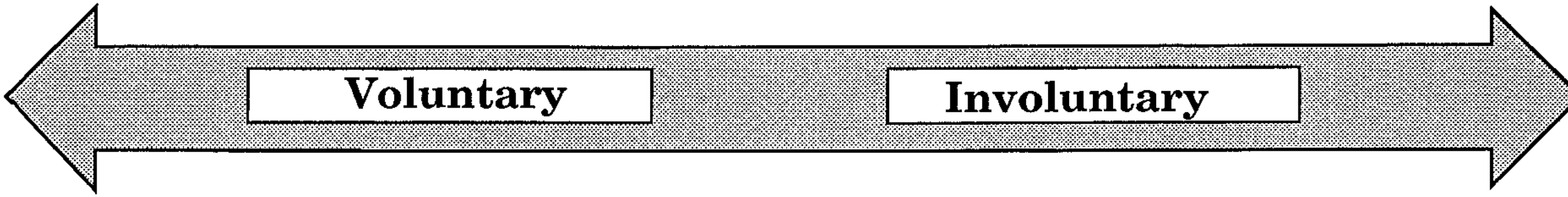
Finally Kenton made use of the ground water flow map he had been prompted to make by Colonel Banks several weeks earlier. It significantly narrowed down the field of sources for the contaminants out in Kuma Estates. Most of the big names like Petefish Brothers, the Shoop Feed and Agri-Center and Erinakis Scrap Lead were downgradient from the Johnson's neighborhood, so it was highly unlikely that any of them was the source. The Kuma County Incinerator and Landfill was a possibility, but Kuma Estates is on the edge of the buried valley. Contaminants from the landfill must be diverted quite a distance to show up so far to the west. The source had to be beyond the rim of the buried valley, in the uplands, somewhere to the west or northwest. That narrowed it down to some of the farms out that way, a handful of light industries or maybe T. Mack Aero-Plastics.

Careful not to charge ahead too hastily, Kenton made a call to the state SCS office to discuss his suspicions with the state geologist, Ed Stearns, who might be able to give him some help.

* * * * * *

		Advantages	Disadvantages
Passive	Sheet Piling	• Established technique • Contractors are readily available • Relatively inexpensive • Low maintenance requirements	• Limited to unconsolidated materials • Wall may be susceptible to corrosion • Leakage may occur when improperly installed
Passive	Grout Curtains	• Established technique • Low maintenance • Wide range of grouts available • Effective in consolidated and unconsolidated formations	• Expensive • Difficult to evaluate Effectiveness • Limited number of experienced construction contractors
Passive	Slurry Trench Cutoff Walls	• Relatively easy construction method • Very little maintenance • Long service life	• Limited to unconsolidated formations • May be moderately expensive
Active	Hydrodynamic Control	• Less expensive than passive containment methods • Offers a high degree of flexibility in its design	• Operation and maintenance costs are high • Monitoring costs are high

Figure 9-3. *Summary of advantages and disadvantages of remedial methods for physical containment of ground water.*



Educational

Public Presentations
School Programs
Household Chemical Cleanup Days
Waste Oil Collection Programs
Free Water Analysis Programs
Aquifer Hotlines
Publicity Tactics
- -Bumper Stickers
- -Mascots
- -Poster Contests
- -Billboards
- -Aquifer Area Roadsigns

Operational

Contamination Hotlines
Agricultural Practices
- -Soil Conservation
- -Limit Chemical Application

Engineering Practices
Industrial Practices
Contingency Programs
- -Hazardous Material Spill Teams
- -Water System Interconnection

Construction Practices

Economic

Water Use Taxes
Phased Capital Improvements
Purchase of Development Rights
Land Purchase
- -Watersheds
- - Sensitive Areas

Public Land Retention
Eminent Domain
Conservation / Scenic Easements
Restrictive Covenants
Property Tax Incentives
Tax Abatements
- -Water Conservation
- -Water Saving Device Installation

Letters of Record to Landowners

Regulatory

Special Management Districts
Zoning Regulations
- -Special Zoning & Overlay Districts
  - •Floodplain
  - •Conservation
  - •Well Field
- -Permits and Waivers
- -Transfer of Development Rights
- -Performance Standards
- -Cluster Zoning
- -Reduced Density Zoning

Subdivision and Planned Unit Development Ordinances
- -Building and Landscape Codes
  - •Double Plumbing
  - •Grading & Soil Restoration
  - •Water & Sewer Hookup

Well Development Standards
- -Aquifer Penetration Restrictions

States and Federal Designations (Critical Areas or Sole Source)
Watershed Rules & Regulations

Figure 9-4. ***Motivational spectrum of management mechanisms.***

Where to Find Help

In tackling ground water problems, there are many cases where a basic understanding of the system is enough to solve the problem. When the problem is complex, however, the services of professional hydrogeologists, geologists, or engineers may be needed. Most often the state geological survey or department of natural resources are the best sources of information for locating these services. This, of course, varies from state to state. State offices and National Technical Centers within the Soil Conservation Service could certainly provide assistance or locate someone who could. US Geological Survey offices in each state are always willing to supply available information. On a more local level, the Engineering and Water Supply/Water Treatment staffs of counties, local municipalities or townships may be notified, if only to inform them of the need for more information. The county representative of the Extension Service is always someone to contact. Figure 9-5 presents a list of national organizations that may be contacted for information about technical consultants.

FEDERAL AGENCIES

United States Environmental Protection Agency
United States Geologic Survey
Soil Consevation Service

STATE AGENCIES

Department of Natural Resources
Department of Water Resources
Environmental Protection Agency
Geologic Survey

LOCAL - COUNTY - REGIONAL

Health Department
Water Department
Ground Water Management District
Soil and Water Conservation District
Planning Commission
Universities

The following organizations may be able to furnish information regarding technical consultants:

American Institute of Professional Geologists (AIPG)
P.O. Box 957
Golden, CO 80401
(303) 279-0026

Association of Engineering Geologists (AEG)
8310 San Fernando Way
Dallas, TX 75218
(214) 321-1061

National Society of Professional Engineers (NSPE)
2029 K Street, N.W.
Washington, D.C. 20006
(202) 463-2300

National Water Well Association (NWWA)
500 W. Wilson Bridge Road
Worthington, OH 43085
(614) 846-9355

Figure 9-5. *Sources for information, guidance, and technical consultants.*

Epilogue

"Well, you can't expect to play golf twice a year and expect to be any good at it!", Mike Kenton said to himself as he watched his ball slice off the fairway and into the rough. He remembered back in May what a great summer he thought it would be for improving his golf game. Somehow though he had gotten all caught up in the "contamination craze" as they referred to it down at the office and his second game of golf didn't come until now, early September. By now he really didn't even want to play that much, but something he couldn't explain had drawn him out. All summer long he had felt a strange pull from this area. He had driven by the golf course, just a mile or so away from Kuma Estates, so many times while trying to put together clues about the well contamination. He had even considered the golf course as the possible source of contaminants because of all the chemicals they must use to keep the place looking so good. He had checked a soil map of the area, however, and had found that the course was located right on top of a clay-rich soil overlying glacial till. The source of contaminants had to be in a place where there was rapid access to the aquifer below—the golf course wasn't the place.

All the information he had acquired had pointed to this side of town being the source of contamination. He was the first to admit that he had become consumed with finding the source of contamination in Kuma Estates. At times he felt like a TV detective unravelling a mysterious murder. Outside of learning a great deal about ground water, however, all his efforts had been fruitless. Here it was September and still nothing. The past month had been incredibly dry which didn't help. The contaminant concentrations in Kuma Estates seemed to rise to detectable limits only after it rained.

Sure, there was contamination coming from the Kuma County Incinerator and Landfill and from Erinakis Scrap Lead, but it wasn't affecting this side of town. Monitoring around those sites had defined contaminant plumes migrating along the center of the buried valley. Modeling had also shown that a leachate plume from the landfill was moving toward the Jefferson City Municipal well fields at a high rate. Low concentrations of some substances were already being found in a few of those wells. If something wasn't done to remedy the situation, the major portion of the plume could arrive in a year or two. Jefferson City was luckier with the Erinakis Scrap Lead contamination. It was moving south and away from the City and probably into someone else's back yard.

Anyway, Kenton had tried to put all this contamination business out of his head for the day. His anxiety level had not gone down much though. He was not only playing a lousy game of golf, but he was being beaten unmercifully by his partner, Carin Stevens. He had seen her a few times since the fair and had asked her to join him. He thought this would be a good excuse to spend some time with her under the guise of showing her a few of the finer points of the game. He was wrong on both counts. He hardly got to see her at all; she was always far ahead of him on the fairway and he was always looking for his ball in the woods!

Eventually he caught up with Carin on the tee of the 16th hole. She drove the ball long and hard, straight down the center of the fairway. He couldn't get over how hard she could hit the ball! He teed his ball up and tried to clear his mind of all extraneous thoughts. Somewhere at the peak of his upswing—out of nowhere—the word, "transmissivity", popped into his head. His ball sailed off into the woods to the right of the fairway. Trying to cover his embarrassment with a little humor, he told Carin he'd meet her at the 19th hole and walked off in the direction of his ball.

He found it a few minutes later in a low spot in the woods about 50 yards off the fairway. As he eyed-up his shot he looked off to the right and saw something he'd never noticed before. It was a couple of sheds which were surrounded with all kinds of equipment: lawnmowers, garden tractors, a couple of spray rigs, and numerous barrels. "Must be the greenskeeper sheds," he said to himself as he put his concentration back on the ball in front of him. He reeled back and then suddenly at the top of his stroke, a question came to him. "Barrels of what?" Aborting his swing, he looked back at the sheds again. Suddenly he reverted to Mike Kenton—Ground Water Detective!

He needed a closer look, but didn't want to draw too much attention to himself or seem like a snoop. He glanced around to see if anyone was watching, then picked up his ball and flung it toward the shed. It landed a few yards to the right and a little beyond. He walked past the equipment and a row of hedges acting like he was looking for his ball. As he came around the corner of one of the sheds, he saw something he simply couldn't believe—a miniature dump! Strewn all about in an area just a few yards square were dozens of drums and cans—some empty and some open and partially filled. There were old containers of paint, gas and oil, engine degreasers, and herbicides and lawn chemicals with names Kenton couldn't even pronounce. A hose led from the building over to the edge of the mess where there was a low spot with no grass growing. The ground was stained and saturated with what looked like oil. "This must be where someone rinses off the mowing and spraying equipment," Mike thought. Looking a bit closer, Kenton saw a piece of old clay tile sticking out of the ground. This is what he had been looking for!

Needless to say Kenton finished the last two holes under par, made a date with Carin for the following Saturday night, and was back at the office within the hour. Remembering that little piece of clay tile, he went to an old filing cabinet in the back room. He rummaged through file after file dating back to the late 1930's and early 40's. Finally he pulled out a file that contained a very interesting map. It was a map of a farm owned by Hiram Jefferson, great-grandson of Finneus Jefferson, founder of Jefferson City. Back in 1939 he had installed several drainage tiles on his land and this map showed where they were. The interesting thing was that this farm was eventually sold and made into the Kuma View Golf Course.

He went to another file cabinet and pulled out another map which showed the layout of the golf course. He compared the two maps and at that moment, things became crystal clear. The drainage plan showed the location of clay tile traversing the right side of the 16th fairway and going right beside the area where the greenkeeper's shed was. Following it on down, he found that this tile emptied into a surface drainage ditch about three quarters of a mile away in—you guessed it—Kuma Estates!

Pulling out his soil and glacial geology maps, Mike checked the materials in the Kuma Estates area. Sure enough, a major portion of the development was located over a zone of sand and gravel representing a buried channel of some kind connected to the main buried valley. The drainage ditch was located right on top of these deposits and ran right by the Johnson residence as well as the other homes, which had experienced contaminated well water earlier in the season.

He had put it all together. Chemicals being washed off the equipment, rinsed from containers, and maybe even just dumped out on the ground out at the golf course, were entering this tile. The tile was dry most of the time, but when it rained these substances were being flushed through and carried to the drainage ditch a mile away. There they quickly infiltrated into the sand and gravel below and entered the wells, many of which were located right beside the ditch. People who were pumping a great deal of water for watering their lawns and gardens were inducing infiltration from this ditch. Kenton made a quick sketch of the scene which is shown in Figure E-1.

Feeling like he'd just rung the bell at the Kuma County Fair, Kenton leaned back in his chair and relaxed. He thought about how incredible it was that something as simple as an old farm tile appeared to be the key to the whole problem. Who would have thought that someone at the golf course could be so careless as to simply be indiscriminately dumping or rinsing potentially hazardous chemicals onto the ground. It was a case of an old forgotten land use colliding with a poorly managed new one.

Now it was a matter of reporting the situation to the conservation district supervisors who could then advise him on what to do next. Most likely the proper regulatory authorities would first be contacted, some samples would then be collected and analyzed and a technical consultant would need to study and verify Kenton's findings. Once that was done the wheels could be put in motion to get the problem remedied.

It had been a long summer indeed, but Kenton's persistence in the matter had paid off. He could always work on his golf game next spring. Putting his feet up on his desk and looking out the window, he saw Stanley Fiori drive by in his pickup heading for his drill rig up near the landfill. Kenton realized that although a single battle had just been won, the war was far from over. . . .

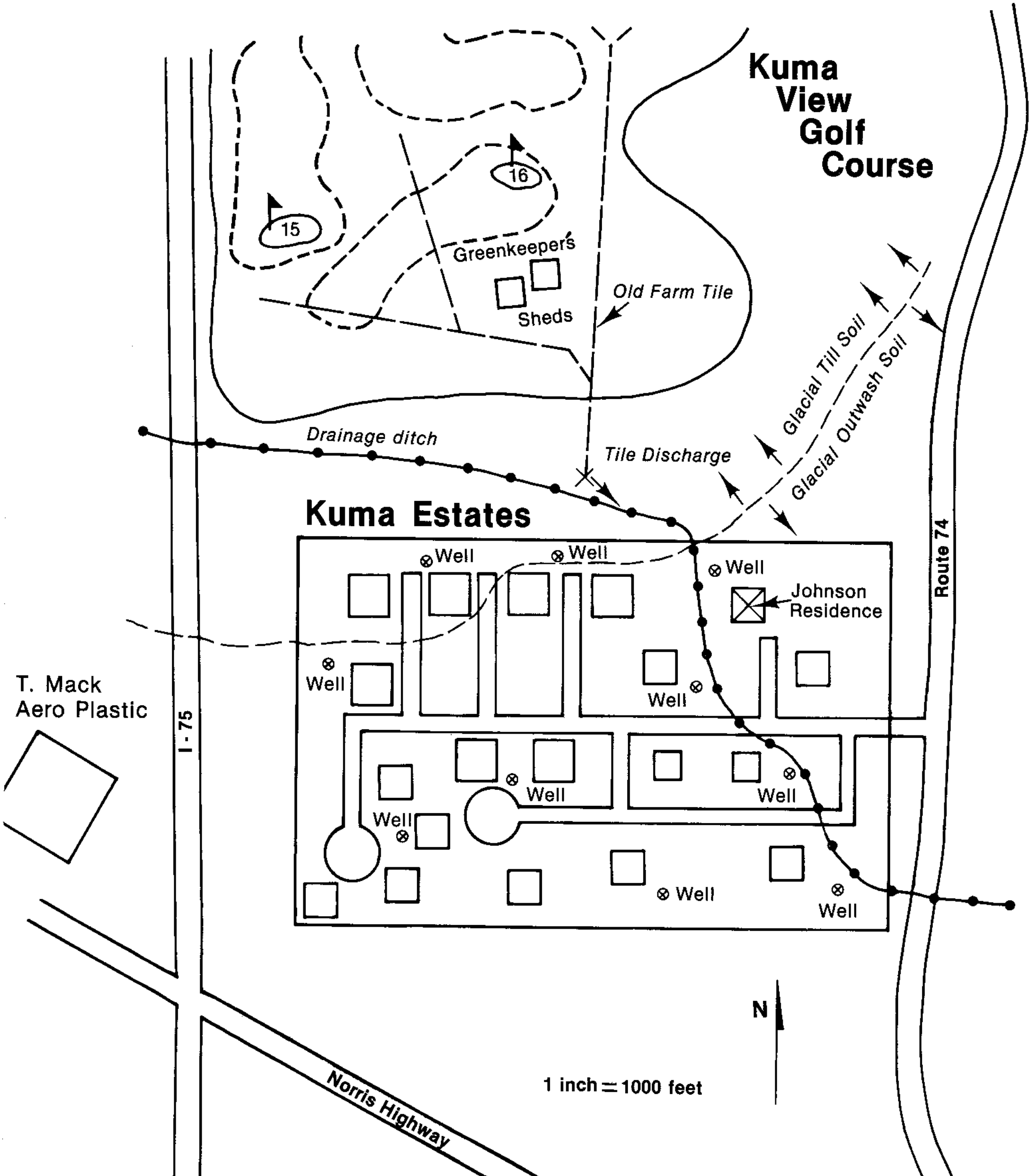


Figure E-1. *Kuma estates ground water contamination scenario.*

Glossary

(An additional glossary is available under separate cover)

Adsorption—the process by which ions from an aqueous solution are attracted to and adhere to solid mineral surfaces.

Aeolian aquifer—an aquifer composed of materials transported and deposited by the wind.

Aerobic—living or ocurring only in the presence of oxygen.

Alluvial aquifer—an aquifer composed of sediments deposited by flowing water in rivers and streams along channels and floodplains. Sometimes also referred to as fluvial materials.

Anaerobic—able to live or occurr in oxygen-free conditions.

Anisotropic aquifer—an aquifer in which the magnitude of hydraulic conductivity varies with direction.

Aquifer—a soil or rock formation which is capable of storing and transmitting a usable amount of ground water to the surface.

Aquiclude—a layer or zone unable to yield water.

Aquitard—localized lens or layer in a formation which is very slowly permeable and hinders the free movement of water.

Attenuation—the process by which the concentration of a pollutant or contaminant decreases or is removed from solution as it moves through an aquifer medium.

Baseflow—the ground water contribution of stream flow.

Braided stream—a stream flowing in several dividing and reuniting channels.

Buried valley—a pre-existing bedrock valley which has been left buried under unconsolidated glacial deposits.

Capillary fringe—the transitional zone between the saturated and unsaturated zone where the pore spaces are partly filled with water.

Columnar joints—joints which form polygonal or hexagonal columns in igneous rock as a result of contraction during the cooling process.

Cone of depression—the drawndown potentiometric surface surrounding a well or well field.

Confined aquifer—an aquifer where the water table is separated from the atmosphere by an impermeable layer of material. Also called an artesian aquifer.

Contact spring—a type of spring which usually occurs where a mass of permeable rock or unconsolidated material overlies another mass of impermeable material.

Contaminant—any solute or potential pollutant which is introduced into or activated within an aquifer and which reaches an objectionable level.

Denitrification—the principal process by which nitrogen is removed from effluent and given off as gaseous nitrous oxide or elemental nitrogen.

Depression spring—a type of spring which occurs where the topography actually dips below the main water table forming marshes or small ponds.

Depression storage—runoff water that becomes trapped in puddles.

Diagenesis—the process by which unconsolidated sediments are physically and chemically altered to form consolidated rock.

Drawdown—the drop in the water table in the vicinity of the well upon pumping.

Drift—unsorted unconsolidated sediments deposited directly from glaciers. Includes till plains, kames and moraines.

Effluent stream—a stream which gains ground water. The baseflow contribution of the streamflow increases as one moves further downstream. Also referred to as a gaining stream.

Elevation head—the fluid pressure measured at point above a datum (usually sea level).

Equipotential line—a line which connects points of equal hydraulic head in a ground water flow field. Analagous to the contour line in the representation of topographic elevation.

Evaporation—the process by which water passes from the liquid to vapor phase.

Evapotranspiration—the sum of evaporation and transpiration.

Fault spring—a type of spring which may originate where rocks are faulted.

Field capacity—the maximum amount of water that can be held in unsaturated soil pores against the force of gravity.

Flowing conditions—confining conditions which result in the potentiometric surface being above the land surface. Ground water flows freely out onto the land surface.

Flow net—a graphical representation frequently used to illustrate ground water flow in the vicinity of a well.

Ground moraine—a sheet of glacial till deposited as a veneer of low relief over a pre-existing topography.

Ground water—the water found below the surface of the earth which fills the pores, voids and fractures within soil and rock.

Hazardous waste—any flammable, corrosive, explosive or toxic waste that may cause or contribute to serious illness or death or that may pose a substantial threat to human health or the environment when improperly managed.

Heterogeneous aquifer—an aquifer in which the hydraulic conductivity varies with respect to position.

Homogeneous aquifer—an aquifer in which the hydraulic conductivity is constant regardless of position.

Hydraulic conductivity (K)—the rate at which water can move through a permeable medium. It is measured in velocity units of length over time and is sometimes referred to as the coefficient of permeability.

Hydrodynamic dispersion—the process by which a solute or contaminant is diluted as it moves through an aquifer.

Hydraulic gradient—the change in hydraulic head over a particular distance in a given direction.

Hydraulic head—the sum of the elevation head and the pressure head.

Hydrogeology—the study of ground water and its relationship to the geologic environment.

Hydrograph—the basic graphical method used to show the discharge of a stream or river at a certain location with time.

Hydrologic cycle—The series of pathways the earth's water may take on its journey from the sea to the atmosphere to the land and ultimately back to the sea.

Hydrologic equation—an equation which expresses the inflow and outflow relationships of the various elements of the hydrologic cycle for a particular region. Also called a water budget equation.

Igneous rock—rock formed from the cooling and solidification of magma.

Infiltration—the movement of water into and through a soil.

Infiltrative capacity—the maximum rate at which infiltration can occur under specific soil moisture conditions.

Influent stream—a stream which loses water to the ground water zone resulting in less water in the channel as one moves downstream. Also called a losing stream.

Interstitial water—the water in the vadose zone above the water table. Also called soil water.

Isotropic aquifer—an aquifer in which the magnitude of hydraulic conductivity is equal in all directions.

Kame—a low steep sided hill of stratified drift, formed in contact with glacial ice.

Karst—Irregular topography developed by the solution of carbonate rock by surface water and ground water.

Lacustrine aquifer—aquifers composed of sediments deposited in lake environments.

Landfill—a diposal site in the land for waste material.

Leachate—the substance that results when a liquid percolates through waste material and extracts dissolved or suspended material from it.

Linear source—contamination which occurs in a linear pattern, such as along highways, pipelines etc.

Loading rate—the rate of application of septic tank effluent on the leach field.

Loess—a post-glacial deposit resulting from wind-blown clouds of silt and dust.

Longitudinal dispersion—the dispersion of a solute parallel to the direction of ground water flow.

Magma—molten silicate minerals beneath the earth's surface.

Metamorphic rock—rock formed from pre-existing rock as a result of high pressure and/or temperature.

Moraine—an accumulation of glacial drift deposited along the wasting edges of glacial ice.

Non-point source—contamination of a regional or areal extent resulting from largely undefined sources.

Outwash—well-sorted sands and gravels transported and deposited by glacial meltwater.

Overdraft—depletion of ground water quantity which generally ocurrs when production exceeds recharge. The resource is not being replaced within any resonable period of time. Sometimes refered to as the "mining" of ground water.

Overland flow—a thin sheet of water that moves across the land surface.

Perched water table—a layer of saturated soil above the main water table.

Percolation capacity—the rate at which septic system effluent can be transmitted through the soil.

Permeability—the measurement of an aquifer's ability to transmit or yield water.

Phreatic zone—the zone below the ground surface in which all the pore spaces are filled with water. Also called the saturated zone.

Phreatopytes—plants with deep tap-root systems that extend below the water table and are capable of transpiring enormous quantities of water back into the atmosphere. Common phreatopytes include willow, cottonwood, saltgrass and mesquite.

Piezometer—an open pipe which is used to measure the elevation of the water table or potentiometric surface.

Plume—a volume of ground water with a high concentration of a certain solute or contaminant which may be absent or in significantly lower concentration in the surrounding ground water.

Point source—A source of contamination which is localized and releases potential pollutants from a single definable location.

Porosity—The percentage of the total volume of material which is void space.

Potentiometric surface—the level to which the water rises in a well. The water table is the potentiometric surface for an unconfined aquifer.

Precipitation—the process by which water vapor condenses into the atmosphere or onto a land surface in the form of rain, sleet, snow or dew.

Pressure head—the pressure exerted by the column of water between the point of measurement and the level to which the water rises in a well.

Primary porosity—the original void space existing within a soil or rock matrix.

Recharge—water entering the saturated zone either directly from the unsaturated zone or indirectly from a surface body of water.

Runoff—the surface contribution of stream flow.

Safe yield—the amount of ground water which can be continually produced from an aquifer, economically, and legally, without having any adverse effect on the ground water resource or the surrounding environment.

Secondary porosity—porosity occurring as a result of weathering, solutioning, fracturing, etc., after the initial formation or depositon of a soil or rock formation.

Sinkhole—a depression in the earth's surface formed from the solution of underlying carbonate rock or other soluble material.

Specific yield (Sy)—the volume of water drained from storage in an unconfined aquifer, under gravity per unit area per unit decline in head. Specific yield is analogous to the storage coefficient in a confined aquifer.

Steady-state flow—conditions where ground water flow is constant. The rate of recharge to the system equals the amount of discharge.

Storage—the net amount of ground water present in an aquifer at a given point in time.

Storage coefficient (S)—The amount of water released from storage in an aquifer of constant thickness per unit area per unit decline in the head

Stream flow—the amount of water traveling along a particular surface drainage route. Streamflow has two major components: runoff and baseflow

Till—an unsorted mixture of clay, silt, gravel, sand and boulders deposited directly from the wasting surfaces of glacial ice.

Transient flow—conditions where ground water flow changes with time. An imbalance between recharge and discharge.

Transmissivity (T)—the rate of flow in gallons per minute through a vertical section one foot wide and extending the full saturated height of an aquifer under a hydraulic gradient of one. The product of the hydraulic conductivity and the saturated thickness of an aquifer. Expressed numerically in units of length squared over time.

Transpiration—the process by which plants give off water vapor through their leaf surfaces.

Transverse dispersion—the dipersion of a solute in a direction perpendicular to the direction of ground water flow.

Unconfined aquifer—an aquifer where the water table is exposed to the atmosphere through a series of interconnected openings in the overlying permeable material. Also called a water table aquifer.

Vadose zone—the zone below the ground surface in which the pore spaces are only partially filled with water. Also called the unsaturated zone.

Valley train deposits—outwash materials deposited in valleys along major drainage routes

Water table—the top surface of the zone of saturation

Xerophytes—plants with shallow root systems such as cactus which are found in arid and drought-prone climates and are especially adapted to minimize transpiration loss.

Zone of influence—the area of an aquifer that is affected by a pumping well or the area in which groundwater is actually flowing towards the well.

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