NATIONAL DRILLING ASSOCIATION

DRILLER'S MANUAL

Preface

The purpose of this manual is to increase the driller's knowledge regarding the earth and the movement of water within the earth. Additionally, the handbook will provide up-to-date information regarding drilling methods and well installation. This information will enable the driller to better participate as a member of a team, together with scientists, engineers, and geologists, to solve some of society's more difficult problems.

As the society in which we live produces more waste materials, some of which contaminate the nations' potable water supply, new sources of water and methods to clean up the polluted water supplies must be found. These difficult problems are being encountered by drillers which require them to understand the nature of the problem in order to be able to suggest suitable solutions.

Finally, the handbook will provide information to aid the driller in making drilling a safe enterprise.

Foreword

In planning this drillers handbook many many thoughts passed through my mind as Dr. Peter Bosscher and I tried to come up with a book that would meet the needs of you people working in the drilling industry today. As you well know this industry is changing so rapidly that what is valid today, six months from now may well be history.

For a long period drilling practices in the geotechnical field stayed pretty standard. Major changes were not forthcoming until the demands of the environmental programs forced us all to learn and deal with many different things in a short time. But as is so often the case in life, the more things change the more they remain the same. Soil and water make mud regardless of what tools you use. This has been a very enjoyable project for me. It was something I think has been needed for quite some time and whomever I discussed the handbook with thought it would be a great benefit to any you who have your hands on throttle.

The material contained in this book has been accumulated from many different sources. Until we began work on this, I had no idea how much has been written about this industry over the years. Unfortunately very little of it has ever been put in the hands of the drillers in the field which may explain why once a driller learns something its very difficult for him to change gears. Information is so short they don't want to lose it!

This is not a how to book. This is not a book that tells you what you will meet in your day to day problems. It is a book that tries to explain to you what the drilling industry is, the wide spread of influence it has and what the many different parts that make it up.

The drilling business is a practice of basics. These basics are what make good drillers regardless of the many different machines or tools we use. Any person in this business classified as a senior driller, (old driller or whatever you might be called) to carry that title, should have a basic knowledge of all dealing practices and procedures. That's one of the things we have tried to accomplish with this book. Its
important for you, the driller, to know how air and mud rotary works. Its important for you, the driller, to know what reverse circulation is, how cable tool rigs operate and what makes them so unique that they are still the rig of choice many places. When you meet other drillers, and you will, they will say I do this and that and they will ask what you do. With a basic knowledge of industry you at least know what they are talking about. While you may never have done what they have done, after reading the book you will probably know more of their work than they do of yours. Having a basic understanding of their problems so you can relate can only help you learn to do your work better and quite possibly get you some free beers as a bonus.

This philosophy holds true for including the many testing procedures and the various sampling tools that are described in this book. Some of these tools you may never see but you will at least know what they are and you will at least know what they do. With this knowledge you can perhaps protect some more educated soul from making some costly errors. This is a proper thing for drillers to do you know.

In today's drilling market you, the driller, have to deal directly with the engineer, or the hydrogeologist. The days when he would work through your boss or an intermediary and you could say, "I don't know anything about that talk to boss" are gone. In the field you are the boss and you need to have the skills to deal with these people using the same language they work in. It's important for you to know, when they talk about "cone of depression" or "permeability" what these terms mean. Drilling is like everything else in that if you can help them get what they are looking for you will probably get yours as well. If you have a basic understanding of what the engineer wants, then you as a driller can find a way to produce that result. They can in turn help you solve your problems by giving you an understanding of what groundwater movement is, what it does, and how soil reacts when groundwater conditions change. Today it takes more heads and more hands to solve drilling problems than ever before. Anyone in this industry today needs to have access to all the knowledges and skills that can be reached.

Those that have gone before us, had they had a book like this to work with, probably could have trained us a lot better. At least it would not have taken us nearly as long to learn that we have to keep on learning. As you read this book and use it remember, it's not just for studying to pass driller certification exams it's for your everyday work. Hopefully when you have a problem you will glance into this book to seek an answer. Should you do that you will have taken a great step toward solving your problem as you will be opening yourself to new and yes, maybe old ideas. You will also look at it and say to yourself somebody did a hell of a lot of work figuring this out and you will learn. The techniques or tools that you come up with will be the next chapters to add to this book for this book is intended to be a food for thought. It is intended that it will grow with you and the industry. No one book will be written for the drilling industry for it is made up of too many individuals, each who in their own way write the chapters of drilling. This is truly mens' work.

I had an enjoyable time working with Professor Bosscher and the university staff in preparing this. The guidance for the program comes from them. We went through reams and reams of paper trying to get to things that would be practical for you to use. We also spent anxious moments trying to meet the deadlines that were imposed upon us. But in the long run we all feel that we have done a significant service to this industry and we hope you will appreciate it.

Thomas C. Ruda  
Chicago Chapter, President  
National Drill Contractors Association
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American Association of State Highway and Transportation Officials
444 North Capitol Street, N.W., Suite 225
Washington, DC 20001

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GLOSSARY: APPENDIX A Part 1; APPENDIX A Part 2; APPENDIX A Part 3  
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CHAPTER 1.  

BASIC GEOLOGY AND HYDROLOGY

For years nearly everyone took water for granted. Few persons worried that water resources had finite limits, that they could be lost to contamination or outright removal, or that the pressures of a burgeoning population would create physical and chemical stresses on these resources never dreamed of only a
generation ago. Since the 1960s, however, a keen awareness of the fragility of these resources has
developed throughout the world. Once a resource is endangered by the impact of man, society can be
required to expend large sums of money and time to determine what the problems are and to develop
potential solutions.

Water is one of the fundamental resources. It is at once one of the most common substances and one of
the most unusual. Although its chemical formula is deceptively simple, the effect of water on almost
everything in our environment is far more important than might be imagined.

1.1. Properties of Water

Water is often called "the universal solvent". It has the extraordinary ability to dissolve a broad range of
substances. In fact, it dissolves more substances in greater quantities than any other liquid. The salinity
of the world's oceans is a direct result of water's ability to dissolve rock materials as water flows
overland to the sea. Eventually, an element such as calcium becomes so abundant in sea water that it
precipitates out, forming crystals of the mineral calcite. So much calcite is precipitated that thick layers
of a sedimentary rock, called limestone, form on the ocean floor. This rock may later be uplifted by
large-scale geologic forces to form part of the land areas of the world. If conditions are just right, the
limestone may in time provide huge reservoirs for underground water resources.

Water has the highest heat of vaporization of any liquid. In other words, huge amounts of heat energy are
required to evaporate even small quantities of water. The subsequent release of this energy through
condensation during rainstorms provides an important energy source for driving weather systems.

Because of water's high heat capacity, the presence of oceans, lakes, and large rivers prevents extreme
fluctuations in local temperatures. Coastal communities have much more uniform temperature regimes
than do areas farther inland. Within the human body, water is critical in maintaining uniform body
temperatures. Without the large volume of water in our bodies (approximately 75 percent), we would
warm up or cool down much more rapidly than we do.

Water has other unusual physical and chemical characteristics that play a large but often unrecognized
role in our daily lives. For example, part of any volume of water has a natural tendency to break down
spontaneously into hydrogen (H+) and hydroxyl (OH-) ions. This process is called dissociation. When an
abundance of these charged ions are available, an electric current can be transmitted through the liquid.
The dissociation process is enhanced when an acid is added to water. For instance, automobile batteries
contain an electrolyte (acid added to water) which contains abundant H+ and OH- ions. The electrolyte
permits batteries to store and give up electricity rapidly.

1.2. Water and Our Environment

The Earth's atmosphere contains from 0.02 to 4 percent water by volume, depending on location. In
addition to providing sources for precipitation, atmospheric water vapor affords two powerful safeguards
for life on Earth. First, it intercepts some ultraviolet (short-wave) radiation from the sun. It is this type of
solar radiation that produces skin cancer in humans. Second, much of the heat that the Earth receives
from the sun is radiated back into space. Atmospheric water vapor, however, intercepts some of this
potential heat loss and redirects part of it back to Earth, while part is retained in the atmosphere. These
phenomena produce a warm atmospheric envelope around the Earth that prevents large daily temperature
fluctuations similar to those found on the moon.
Another unusual feature of water related to its molecular structure is the great capacity of water molecules to cling to one another. This characteristic, called hydrogen bonding, gives water the highest surface tension of any liquid. Therefore, it is relatively difficult to pass anything through a water surface. This physical property gives water vapor its tendency to form droplets when condensing in the atmosphere.

Unlike most other liquids, water reaches its maximum density at 39.2°F, which is well above its freezing point of 32°F. As a result, lakes in colder climates do not freeze from the bottom up, but instead are covered each winter with a relatively thin layer of ice. Biological activity would virtually cease in lakes if they were filled with ice each winter. In the colder climates of the world, air temperatures pass back and forth through the freezing point many times each year. Water in shallow cracks and crevices of rocks found in these climates freezes and thaws as many as 70 times annually. The force exerted by the freezing water, as much as 30,000 psi is sufficient to crack even the most durable rock. This process, called frost wedging, can cause extensive destruction of large rock masses. Eventually, these rock materials are reworked by the agents of erosion-running water, glacier ice, and wind-into various kinds of unconsolidated sediment. Some of these sediments serve as storage sites for groundwater.

Water plays a major role in virtually every aspect of human life. Regrettably, too few persons understand the physical and chemical properties of water well enough to effectively solve urgent and nearly universal problems relating to its cost, availability, distribution, and contamination. Water problems of any type stem largely from lack of knowledge and, therefore, from mismanagement of the natural system. These problems are intensified by the technological impact of man on that system.

Water is such a fundamental part of the Earth that anyone studying water must first understand how the Earth evolved and the changes that have taken place in and near the Earth's crust over the last several billion years. In the past, geologists thought the Earth was more or less static; that is, its topographic features and internal structure remain relatively constant. Recent discoveries now demonstrate that the Earth is a dynamic planet. Subtle changes are occurring constantly in the arrangement of continents, the building and destruction of mountain chains, the creation and movement of the sea floor, and even the climatic conditions affecting the planet.

By the late 1960s and early 1970s, geochemists could determine the ages of rocks by comparing the ratios of certain radioactive elements in the rocks. These radioactive substances decay or change spontaneously to other substances at a constant rate. By measuring the relative quantities of the original and new materials, geochemists can approximate the ages of many rocks. Some of the rocks recently dated originated about 4 billion years ago, shortly after the formation of the Earth.

Until a few years ago scientists knew little about the composition of the ocean floor because of its inaccessibility. Recent investigators, using new ships capable of remaining stationary and drilling in water depths of 23,000 ft or more, have discovered that the ocean floor consists almost entirely of two rock types, basalt and gabbro. Continental land masses, however, contain numerous rock types. This discovery suggests a completely different mechanism for the origin of ocean basins as contrasted with continents. Therefore, it is best to examine the Earth from its very beginning to understand the origins of groundwater systems.

How did the Earth form, what was it like in the beginning, and what physical changes have occurred over the last several billion years? Geophysicists believe that the Earth formed from the remnants of an exploded star, a supernova. In time, individual pieces of rock fell together by gravitational attraction.
Other bodies in our solar system formed in a similar manner. It is not known how long the Earth took to form, but it is known from the ages of rocks that the Earth is about 4.6 billion years old.

At its inception, the Earth most likely did not have an atmosphere, hydrosphere, or the familiar crustal components seen today. No distinct continents, ocean basins, or mountain chains existed. Probably the entire surface was a heterogeneous mass of rock debris. Thus, the structure of the Earth's atmosphere and surface has changed profoundly through time. It is unlikely that large volumes of free water existed on the Earth’s surface at the time of the Earth's inception. If the Earth originally had little or no water, and water now covers three-fourths of the Earth's surface, what geologic processes produced the gigantic volumes of water available today?

When plate collisions began and magma formed in the subduction process, gases were produced in the accompanying volcanic eruptions. The principal gas released was water vapor because hydrogen and oxygen exist in the chemical structure of many rock-forming minerals. When these rocks are melted, hydrogen and oxygen are released and unite quickly in the atmosphere to form water vapor. Over geologic time large amounts of oxygen were also contributed by photosynthesis which readily combined with hydrogen liberated in volcanic eruptions. The water formed from the melting of rocks is called juvenile water; i.e., water never before on Earth in a combined form. Another source of water comes from the destruction of rocks at the Earth's surface by a process called weathering. Some rocks originate under high pressure and temperature at great depth in the Earth. Once exposed, these rocks are out of their original chemical and physical equilibrium, leading to gradual disintegration and the release of certain gases, including water vapor.

Great changes were occurring in the character of the atmosphere as the Earth's crust was evolving. Since the mid-1950s, most scientists have believed that the Earth's early atmosphere was devoid of oxygen. Many forms of geologic evidence also suggest that the atmosphere was in a chemically reduced state and consisted almost entirely of nitrogen, methane, water, and possibly ammonia. It is assumed that any hydrogen and helium present when the Earth formed would have been lost shortly thereafter because these gases are unusually light. The little oxygen that may have existed came from the breakdown of water vapor in the upper atmosphere. Because it quickly combined with ammonia and methane, no free oxygen was present. About 1.9 billion years ago, oxygen began to be increasingly important as a part of the atmosphere. Sedimentary rocks in Africa contain evidence of primitive organic matter that is approximately 2.7 billion years old, which indicates the photosynthetic processes had started by that time. Plants use atmospheric carbon dioxide during photosynthesis and give off oxygen. As plants proliferated, photosynthetic activity contributed increasing amounts of oxygen. There is little doubt that the Earth's atmosphere is constantly changing in response to emissions of volcanic gases during subduction processes, biological activity, and the weathering of rocks at the Earth's surface.

The composition of today's atmosphere is given in Table 1.1. The only component that appears to be changing rapidly (in terms of man's time on Earth) is the carbon dioxide content. Since the start of the Industrial Revolution, huge amounts of fossil fuels have been burned to provide energy for industrial expansion and better living standards. In the burning of coal, oil, wood, and other fossil fuels, carbon dioxide is released while oxygen is consumed. So much carbon dioxide has been released in the 20th century that some scientists are worried that it is trapping more of the Earth’s heat in the atmosphere. Rather than escaping into space, some of this extra heat is radiated back to Earth by the carbon dioxide and may cause a worldwide increase in temperature, leading to partial melting of the continental ice sheets on Greenland and Antarctica and massive flooding of coastal communities. Another adverse impact caused by burning large amounts of fossil fuels is the acidification of rainfall over large areas of industrialized countries. Biological activity in lakes has either ceased or is limited seriously where the
bedrock does not naturally buffer (neutralize) this rainfall; for example, in Canada, New England, northern Minnesota, Florida, southern Norway, and Germany. In time, this phenomenon, called acid rain, may increase significantly the acidic of near-surface groundwater.

All igneous and metamorphic rocks exposed at or near the Earth's surface are in an unstable chemical and physical condition, and over geologic time these rocks breakdown into finer and finer components. Destruction of rocks and the redistribution and deposition of the rock particles play a significant role in producing three of the four major types of aquifer systems - alluvial, sedimentary, glacial, and igneous/metamorphic. These particles are entrained and redistributed by the three agents of erosion - wind, running water, and glacier ice. Running water is the most effective of these agents because it operates continuously over most land areas of the Earth. Furthermore, it acts both as the primly agent in the creation of alluvial aquifers and is a major force in building or altering other types of aquifers. Before any major removal of a rock mass can take place, however, it must be broken down into particles that can be carried by these agents of erosion. These processes are called rockweathering.

### Table 1.1. Composition of the Earth's Atmosphere

<table>
<thead>
<tr>
<th>Gas</th>
<th>Volume (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N₂)</td>
<td>78.1</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>20.9</td>
</tr>
<tr>
<td>Argon (Ar)</td>
<td>0.934</td>
</tr>
<tr>
<td>Water (H₂O)</td>
<td>up to 1.0 (variable)</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>0.031</td>
</tr>
<tr>
<td>Neon (Ne)</td>
<td>0.0018</td>
</tr>
<tr>
<td>Helium (He)</td>
<td>0.00052</td>
</tr>
</tbody>
</table>

1.3. Weathering

Weathering is the in-situ physical disintegration and chemical decomposition of rocks in response to the environmental conditions found at or near the Earth's surface. In general, the higher the temperature at which a rock formed, the more unstable it will be at the Earth's surface. Granite, which crystallizes from magma at approximately 1,110°F, is much more resistant to weathering than basalt, which forms at 2,190°F. Thus, the weathering rate depends on the temperature at which the rock formed, as well as climatic conditions, the availability of water, its chemistry, and rate of movement, and the chemistry of minerals making up the rocks. Because water has such a chemical affinity for almost all substances, and because of its unusual physical properties, rock weathering proceeds rapidly in the presence of water. Weathering is not only the first step in the production of alluvial and sedimentary aquifer systems, it is also the process by which soils are produced.

Most rocks decompose or disintegrate by a combination of both physical and chemical processes. Physical weathering is disintegration of rocks in place without associated major chemical change. During physical weathering, Tacks are broken down into numerous small particles having a much larger combined surface area than the original rock. In cold regions, physical weathering is the dominant process; in the rest of the world, chemical weathering is far more important. Once the physical size of the particles is reduced, decomposition is then accelerated by chemical attack on the larger surface area.

Chemical weathering of rocks is most effective in warm, humid regions where it is assisted by organisms. Few common rock-forming minerals can resist chemical decomposition; quartz and
muscovite mica are two notable exceptions. In general, most silicate minerals break down into both relatively insoluble residues (such as clay minerals) and soluble substances which are carried away in solution. Clay minerals are produced through decomposition of feldspars. Limestone, made up of calcium carbonate, can be removed locally in solution if carbon dioxide is present in percolating water. Impurities contained in limestone, in the form of either clay or quartz particles, may remain after the calcium carbonate is completely removed. In general all residual products of weathering are more stable in the presence of air and water than were the rocks from which they came.

1.4. Erosion

The erosion cycle begins with weathering, when rocks are broken down into particles small enough to be carried by running water. Rainwater forms sheetwash, which carries away the smallest particles; sheetwash is water flowing sheet-like across a land surface and generally occurs only during heavy rains. Sheetwash becomes channelized within short distances into rills or rivulets, occasionally into gullies, then into small streams, and finally into rivers.

The most extensive alluvial water bearing strata are found adjacent to rivers flowing from mountainous regions that have moderately dry climates. Sediment accumulations in the floodplains of rivers draining these regions have coarse textures and may have thicknesses of 300 feet or more in certain areas. Streams and rivers transport material in three ways: as bedload, as suspended load, and in solution. Bedload comprises the coarser particles moved along the channel bottom by sliding, rolling, or saltation jumping along the bed, propelled by impacts from other particles. Suspended load is weathered material that a river transports in suspension. A river can always move a fine suspended load, even when bedload movement is nonexistent. The size of the suspended sediment depends primarily on the gradient of the river and generally ranges from claysized particles to coarse sand.

Dissolved material in rivers is carried in solution, usually in the form of ions. Riverwaters are particularly high in dissolved solids in areas of low relief, such as in the Atlantic and Gulf Coast states.

1.5. Alluvial Aquifers

Rivers and streams build groundwater reservoirs consisting of alluvial deposits. Each year about 30,000 mi$^3$ of water falls as snow and rain on the land areas of the Earth. About 30 percent of this water returns more or less directly to the world's oceans by rivers and streams. As this water returns to the sea, it erodes the landscape, deposits sediment such as sand and gravel along river courses, and carries the remaining products of weathering to the sea. Landforms such as floodplains, alluvial fans, and deltas form when rivers deposit miner than erode. Some of the sediment cannot be carried and is deposited as alluvium on a floodplain in the middle reaches of the river. Floodplains form in the valleys excavated by rivers. During peak discharges, the river goes over its banks, the velocity of the water decreases, and suspended sediments are deposited. As the river meanders back and forth, sediments accumulate into an actual plain. Wells drilled in this plain will almost always be successful because the sediments are of similar size (well sorted) and the river provides continuous recharge to the sediments.

If the land surface is uplifted as the river approaches erosional maturity or base level falls because of continental glaciation, the river cuts down into the floodplain deposits and leaves terraces along the valley walls. Terraced valleys are erosional remnants created by periodic downcutting. Once saturated, the sediments comprising the terrace generally become aquifers.
Rivers build one other landform, alluvial fans, that can be important as an aquifer. Alluvial fans are constructed at the base of mountain fronts in relatively dry climates when huge quantities of sediment are carried to the dry valley floors by ephemeral rivers draining nearby mountains. Physical weathering produces large amounts of loose rock material that can be entrained easily into the swift mountain rivers that flow during the infrequent heavy rainstorms. Because the valley floors are nearly horizontal, the sediment load is dumped abruptly as the rivers enter the valleys.

Alluvial fans are important to those interested in groundwater because, along with other valley sediments, fans often represent the only extensive unconsolidated deposits in mountainous regions capable of yielding high volumes of groundwater.

1.5.1. Hydraulic Characteristics of Alluvial Aquifers

The average grain size of river-deposited sediments can vary considerably; floodplain deposits may consist of extremely fine silt, whereas coarse gravel or sand maybe more typical of alluvial fan deposits. Floodplain deposits are usually fine grained, well rounded, and generally well sorted. Therefore, the porosity is excellent but the hydraulic conductivity varies considerably, depending on the average grain size. If the gradient of a river steepens or the discharge increases, the sediment will become coarser and thus the hydraulic conductivity will be higher.

Floodplain deposits are quite uniform except at point bars (inside the meander bends) and at the bottom of the rivers. When a river meanders, coarse sediment accumulates near or on the point bars. As the meanders continue to migrate both laterally and downstream, finer grained (floodplain) material covers the coarse sediment at the point bars. Similarly, bedload is buried during the meandering process. Wells that intersect one or more of these coarse layers have higher yields than those in the finer floodplain deposits.

Alluvial fan deposits are highly irregular in grain size and degree of grain roundness; they are built by braided streams that continually deposit sediment as they flow over the fan surface. The constantly changing paths of the braided streams produce deposits that have an irregular areal distribution. The typical particles in an alluvial fan stream may not be as well rounded as those in a regular stream because the weathered material may not be transported as far before deposition. Fine and coarse sediments are intermixed, and thus the hydraulic conductivity and porosity of fan sediments may not be as good as in river alluvium. It is particularly important, therefore, to drill test holes before designing and constructing wells in alluvial fans. Because of their great thicknesses, these deposits can yield high volumes of water to wells.

Another type of sedimentary deposit occurs in warm, shallow seas when the shells and secretions from marine organisms form organic reefs of calcium carbonate. Great thicknesses of coral can grow if the water deepens slowly. If the water deepens suddenly, the coral will die because of restricted light. Sedimentation on top of the reefs is limited generally to clay particles if near shore, or it may include the skeletal remains of tiny marine organisms if the water becomes deep enough.

Former beach deposits are the most valuable water storage sites because the volume of void space is greatest. Beach sediment ordinarily can store more water per rock volume than any other type of sedimentary rock. Void space in a new beach sand may be as high as 25 to 40 percent. In time, this space may be reduced by settling and rearrangement of the grains, chemical precipitation, or heat, thereby producing a rock formation called sandstone. The physical and chemical changes in sandstone resulting from heat and high pressure produce a rock called quartzite which has virtually no void space.
Sandstone formations are the most important reservoir rock for storing large volumes of groundwater. Some individual sandstone layers are extensive; for example, the St. Peter Sandstone, a major aquifer in the central United States, covers more than 290,000 mi² and averages 80 to 160 ft in thickness.

1.5.2. Hydraulic Properties of Clay

When originally laid down, clay has high porosity. For example, clays now being deposited on the Mississippi River Delta have 90 percent porosity. In time, compaction usually reduces the pore space considerably. Although the volume of void space is relatively high in clays, the actual size of the voids is extremely small. Water is strongly attracted to the large surface area of the clay particles and is less controlled by the groundwater gradient. Thus, water does not move easily through clay sediment. When sufficient and prolonged pressures are applied to clay deposits, the clay changes to shale, which is weakly consolidated and breaks easily along depositional planes. When exposed to water during drilling, some shales can swell to much larger volumes. In shale-rich areas, drilling operations can be severely handicapped or even stopped by swelling shale. If greater heat and pressure are applied, the shale changes to slate, a hard, dense rock with virtually no storage space for groundwater.

1.5.3. Hydraulic Properties of Calcium-Rich Deposits

Initially, inorganic calcium-rich deposits are quite massive and no large amount of chemical or physical action is required to change them to rock after the deposition. Therefore, little void space exists for fluid storage. This is not always true of coral reefs (organic calcium deposits), where initial void spaces occur frequently but are spaced irregularly. Time and other factors, however, do make calcium-rich deposits more rigid and, in some cases, more dense. This type of sedimentary rock, known as limestone, is inflexible and can easily crack when supported unevenly.

Under certain conditions, some of the calcium in limestone can be chemically replaced by magnesium from sea water, either during deposition or after the rock strata formed. Limestone with high concentrations of magnesium is called dolomite. It is not known with any certainty how this process happens, but the addition of small amounts of magnesium causes a pronounced toughening of the rock.

Limestone does not initially offer much of a reservoir for storage, but through secondary solution many deposits of limestone and dolomite can become large-capacity reservoirs for groundwater storage. Other limestones are not cavernous and the only water in them exists in cracks and crevices.

1.6. Glacial Deposits

Glacial aquifers are the second most important category of aquifer systems. Although not as extensive as aquifers found in sedimentary rocks, glacial aquifers occur throughout much of the highly populated regions of northern United States, Canada, and northern Europe.

Pleistocene glaciers have been active over much of the world at various times during the past 3 million years, especially in the Northern Hemisphere. The latest ice advances began about 80,000 years ago, with the ice withdrawing about 8,000 to 10,000 years ago from most areas in the northern United States, southern Canada, and Scandinavia. The most recent Pleistocene glaciers were not as large as some of the earlier glaciers; therefore, they did not completely cover the landscape, but tended to follow topographic lows in a manner similar to modern valley glaciers. These later glaciers left sediments called glacial drift deposited irregularly in both areal extent and depth.
Ice generally flows at rather uniform rates on flat topography; however, when the topography is uneven, the ice will flow faster in the depressions. Entrainment of debris is greatest in these depressions and the ice can deepen valleys to hundreds of feet below sea level. The deep depressions forming the Great Lakes of North America and the fiords of Norway are extreme examples of glacial quarrying in preexisting lowlands.

As the ice flows toward the terminus, glaciers continue to warm and eventually the ice near the margins reaches either the pressure-melting temperature or 32°F. Bottom melting releases debris which is then deposited on the underlying ground surface as the ice flows over it.

1.6.1. Moraine Formation

Rock debris carried well up in a glacier and not deposited as lodgement till from basal debris is eventually transported to the glacier terminus. This heterogeneous material is canted in discrete debris bands above the base of the ice. When the very end of an ice sheet becomes stagnant and temperatures are sufficiently warm to melt the ice at approximately the same rate as it flows into the area, the active ice flowing toward the front is forced upward at angles of 45 to 90 degrees before melting. An ice-cored moraine forms when debris melting out of the ice (till) begins to accumulate near the terminus. More ice eventually becomes stagnant because of the overlying debris, and the active ice is forced to retreat. Debris continues to melt out of the stagnant ice by undermelting and is thereby added to the till blanket. In time, the ice core melts completely, leaving only the glacial sediment on the former land surface.

1.6.2. Depositional Features of Moraines

Unlike sediments deposited by other agents of erosion (wind and running water), glacier ice can entrain and deposit all sizes of sediment in a single land form; huge rocks may be mixed with clay or fine sand. Small lenses of sand and gravel occur frequency in moraines when the newly deposited till is reworked by running water. These lenses are usually limited in size and occur irregularly throughout the moraine. Thick layers of clay without large fragments are also found in many moraines. Because clay is by definition extremely well sorted, the presence of thick clay beds in a typically heterogeneous till matrix should be explained. During the downmelting of an ice-cored moraine, many topographic low spots develop. These are filled with water from time to time by superglacial streams (streams that flow on the ice surface) or meltwater running down from the surrounding slopes into the depressions. Lakes may exist for many years in these depressions if cracks do not occur in the ice underlying the lake bottoms. During the melting season, superglacial streams continually carry sediments to the lakes. The finer or clay-sized material is deposited in the offshore areas, and in time a thick clay bottom may form. Even though a driving contractor may pass through 50 ft or more of clay, additional sand or gravel deposits are likely to be found beneath the clay layer.

1.6.3. Outwash Deposits

During the time a glacier remains in contact with its moraine, meltwater rushing off the clean ice courses through the moraine and picks up sediment. Because the meltwater is free of sediment before reaching the moraine, the transporting capability of these waters is high. Furthermore, the gradient of meltwater rivers is quite steep, usually much steeper than in rivers on land adjacent to the terminus, thus giving them additional capacity to remove sediment from the moraines.
When climatic conditions are favorable for rapid melting, meltwaters entrain gravel-sized debris. Most of this gravel is carried as bedload, that is, the individual stones are transported along the bottoms of rivers and streams. Once the rivers reach the nonglaciated areas outside the terminus where the gradient is much lower, the rivers can no longer transport all the material picked up in the moraine and thus begin to deposit some of it in their channels. Deposition continues until the rivers have the capacity to carry all of the remaining load. Clay-sized materials are usually carried far downstream by the meltwater rivers and deposited away from the outwash aprons. In general, the average particle size in each sediment layer tends to diminish downstream from the moraine.

In time, stratified sand and gravel deposits called outwash build up in front of the moraine. Usually, the sediment aprons extend some 6 to 12 mi outward from the terminus.

Outwash deposits and till sequences are also laid down between moraines by advancing or retreating ice fronts. During a long-term withdrawal, a glacier is periodically interrupted in its retreat by sudden surges of forward movement. Once the advancing ice reaches its new limit, another stillstand of the ice front may occur, and another moraine is created. Several repetitions of advance and retreat may occur before the ice withdraws at the conclusion of the glacial episode. Thus, multiple moraines occur commonly in the terminal areas of many glaciers.

1.6.4. Recognition of Moraines and Outwash Plains

Moraines deposited during the last 10,000 to 35,000 years are relatively easy to identify from topographic maps or by judicious use of a highway map showing lakes. Moraines are generally characterized by numerous abrupt changes in surface elevations over short horizontal distances. The characteristic hummocky or knolly topography develops by uneven deposition of the superglacial debris during melting of the ice core. If the climate is wet, moraines generally have numerous lakes and swamps which form in the abundant undrained depressions. Outwash plains characteristically show only small differences in relief and are marked by shallow, well-rounded lakes. They are recognized easily in the field and on topographic maps by their essentially flat topography. When using a highway map, it must be assumed that the glaciers came from a northerly direction (in the Northern Hemisphere); therefore, the major outwash plains associated with particular moraines must be south of the moraines. Exceptions to this rule do occur, however, especially in glaciated regions near mountains.

1.6.5. Hydraulic Properties of Glacial Deposits

Two types of glacial sediments are generally recognized: till and outwash. Till has been subdivided into two types: lodgement till and ablation till. Lodgement till, often called hardpan by drillers, consists of glacial sediment deposited on the ground beneath the ice when the glacier temperature approaches 32°F. Ordinarily, individual layers of lodgement till are highly compressed, poorly drained, clay-rich sheets from 3 to 30 ft thick; multiple ice advances may increase the total thickness to 300 feet or more. Ablation till consists of material released through surface melting at the glacier terminus. Ablation till is loosely consolidated, clay poor, and contains all sizes of mosey angular to semi-rounded material. This type of till deposit forms huge curvilinear moraine complexes that are found in many northern areas of the United States and Europe.

Till, especially clay-rich till, has lithe pore space because abundant small particles fill in the voids between the larger grains. Thus, there is little storage area for significant volumes of groundwater in till.
Outwash consists of well-stratified and well-sorted silts, sands, and gravels. Outwash sediments are more or less uniform in grain size and contain particles that are usually well rounded, loosely packed, and relatively uncemented; thus, porosities in outwash deposits are unusually high.

Two constructional features of outwash plains are significant. First, the thickness of outwash can vary as much as the relief in the former landscape. In some glaciated regions of North America, old preglacial valleys of the Mississippi, Minnesota, and Ohio Rivers are filled with 250 to 300 ft of primarily outwash material, whereas the adjacent upland surfaces are covered with only 15 to 45 ft of sediments.

1.6.6. Miscellaneous Glacial Deposits

Two other sediment types related to glacial activity are also potential reservoirs for groundwater. The first is loess, a nonstratified and unconsolidated sediment consisting mostly of silt-sized particles of quartz and feldspar. These particles are picked up by wind from outwash plains and deposited downwind as loess at varying distances from the ice fronts. Loess deposits occur extensively because of the abnormally high wind velocities associated with ice fronts, and the ready supply of silt-sized material continuously deposited by meltwater on the outwash plains. Loess found near its source areas may be 150 ft or more thick, but the deposits thin rapidly in the downwind direction.

Valley-train deposits, consisting of coarse sand and gravel, are the second type of sediment indirectly associated with glacial activity. As indicated above, rivers draining the ice fronts carried huge quantities of outwash sand and gravel. At first, the local rivers were unable to carry all the sediment for any great distance, even during the high discharges of the summer season and despite the steeper gradients brought about by the reduction in sea level. In time, the river gradients near the ice fronts were steepened sufficiently by depositional processes for the rivers to carry the available load. Eventually, coarse sands and gravels were transported hundreds of miles downstream via major river systems; some of these sands were transported all the way to the Gulf of Mexico. Today, these valley-train deposits, although localized to a great extent in buried valleys and along existing rivers, represent significant sources for groundwater.

1.7. Rock Aquifers

Locating adequate water supplies in bedrock is extremely difficult because the physical makeup of igneous and metamorphic rocks is generally unfavorable for storage or transmission of economically useful volumes of water. Nevertheless, much of the world's population lives on land consisting of these rock types, and whatever water supplies are available must be utilized.

The major intrusive igneous rock types are granite, diorite, and gabbro. As originally formed, these rocks do not have the necessary hydraulic characteristics required for adequate water supplies. They have a solid structure which precludes both significant water storage and transmission. Extrusive igneous rocks, on the other hand, commonly possess physical features that can provide reasonable-to-large volumes of water. Common extrusive rock types include basalt, andesite, rhyolite, and loosely consolidated volcanic deposits. Unfortunately, extrusive rocks constitute only small portions of the igneous and metamorphic rock areas.

In general, any rock underlying recent glacial drift has a weathered zone. This zone is thickest in the low areas of the preglacial landscape and thinnest on the high areas. In this zone, drillers can expect to encounter marl (calcium-rich clay), iron-rich crusts representing old soil zones, and weakened quartzite,
sandstone, and marble with numerous small-to-large cavities that may be arranged along old depositional surfaces in the original rock. In almost every case, a mushy clay zone of varying thickness exists between the glacial deposits and the more competent underlying weathered bedrock.

Massive basalt flows (extrusive rocks) originate in the interior of some continents as a result of rifting events or so-called hot spots in the upper mantle. Basalt may have high porosity and hydraulic conductivity, depending on the way individual flows cooled or the length of time between flows. The openings in a sequence of basalt flows occur in several ways: as cracks formed during cooling where the hardened crust of a basalt flow has collapsed, as vesicles (gas holes) near the top of each flow, in empty lava tubes, and in alluvial sediments laid down between flows. Vesicles near the top of individual lava flows are a major cause of high porosity and hydraulic conductivity. Wells in basalt have a much greater yield potential than do those in intrusive rocks.

In summary, the success rate for wells in igneous and metamorphic terrains is low. Even when elaborate exploratory methods are employed, the yields from wells may be disappointingly small, and dry holes are common.

CHAPTER 2.

OCCURRENCE AND MOVEMENT OF GROUNDWATER

The majority of the fresh water in the conterminous United States is found in the groundwater. Estimates indicate that groundwater represents approximately 85% of our total fresh water. Approximately half of this groundwater is near surface with an average detention time of 200 years. The other half is much deeper with a detention time of 10,000 years. The second largest source of fresh water is the water found in the Great Lakes.

When precipitation falls to the earth in the form of snow, rain, or hail, some portion of it is intercepted by trees, plants, and buildings. If the storm is brief or of a low-intensity, this water will be evaporated back into the atmosphere.
During heavier precipitation, water (liquid or frozen) does reach the ground surface and can follow several different paths as shown in Figure 2.1. The water that flows overland is called surface runoff. It usually combines with other surface water to form a stream or river. Some of the water may infiltrate the soil and seep downward until it reaches the groundwater table. Some of this water may eventually seep into a stream or river. The relative amounts of surface runoff to infiltration depends on the amount of water already present in the soil. During severe storms (or in the north during the early spring when the ground is frozen) little or no water may infiltrate the ground. These are the times when flooding is likely. Typically water is introduced to the soil by infiltration and stream flow, however once the water enters the soil, it exists in several different modes as shown in Figure 2.2. This commonly used classification indicates that water is found in two major zones in the soil—a zone of vadose water and a zone of phreatic water.

![Diagram of subsurface water](image)

**Figure 2.2. Classification of subsurface water. (After Davis and DeWiest, 1966)**

In the vadose zone, three separate types of water exist: soil water, intermediate vadose water, and capillary water. The soil water is the primary water used by plants. The depth of the soil water zone varies from 3 to 30 feet. The intermediate vadose water zone merely represents the region between the soil water zone and the capillary water zone. The capillary water zone (sometimes called the capillary fringe) is the zone where water is literally pulled upward by capillary action (which depends on the surface tension between water, soil particles, and air). The height of capillary rise depends on the size of the smaller grains of the soil. Capillarity is not effective in coarse grained soils whereas water can be pulled up 30 feet or more in some clays.

The groundwater table lies at the bottom of the capillary zone and separates the vadose water zone from the phreatic water zone.
If a well were drilled through the vadose zone, into the phreatic zone, the water level in the well would mark the location of the groundwater table and the top of the phreatic zone. Water below the groundwater table is generally called groundwater. Davis and Dewiest refer to this water as phreatic water meaning water that enters freely into wells. This handbook will use groundwater instead of phreatic water, referring to water that can be removed by wells. It is important to note, groundwater therefore does not include water above the groundwater table.

An aquifer is historically defined as a geologic formation that will yield useful quantities of water for a water supply. The term is relative to other available sources of water and to the quantity of water required. The nearly synonymous terms water-bearing material and water-bearing zone may be defined in the broader sense as being any geologic formation or stratum, consolidated or unconsolidated, or geologic structure, such as a fracture or a fault zone, that is capable of transmitting water in sufficient quantity to be either of use or of concern. Such a formation contains pores or open spaces between the minerals grains that are filled with water. The ability of a formation to hold and transmit water depends on the size and number of pores in the geologic formation. Some formations may have a large pore volume (some clays for example) however the are unable to transmit water due to their small pore openings and therefore are not classified as aquifiers. Ordinarily a clay or shale formation is nearly impermeable and is called an aquiclude. Formations which yield some water but not enough to meet modest deems are termed aquitards. These terms are not absolute and may depend on the availability of water in a given region.

Water exists in aquifers under two different physical conditions. The most common condition is when the water table is exposed to the atmosphere (via the pores of the overlying soil). This type of aquifer is called an unconfined aquifer or water table aquifer. The water table is the upper surface of the zone of saturation in an unconfomed water-bearing material. The water table is the imaginary surface in an unconfined water-bearing material along which the hydrostatic pressure is equal to the atmospheric pressure. In coarse grained soils, the water table is near the top of the saturated zone. A perched water table occurs where a layer or lens of low permeability material lies within an unsaturated permeable material and restricts the downward movement of water sufficiency to create a localized saturated zone above the general water table. In certain soils a layer of low permeability occurs in the subsoil that prevents downward percolation of water sufficiently that during wet periods a temporarily saturated zone develops. The top of this intermittently saturated zone is referred to as the seasonal high water table. It may or may not be perched. A perched zone of saturation that is sufficiently permanent and transmissive may be called a perched aquifer.

Although subsurface water does not occur in underground streams (except in some cavernous formations) as popularly misconceived, groundwater flow is variable throughout the subsurface. The natural variability of rocks and soils causes variations in hydraulic conductivity both within a water-bearing material and from one water-bearing zone to another. In unconsolidated materials where primary porosity is dominant, groundwater flow is generalized throughout the material because the interstices are numerous and close together. However, within a generally fine grained material there may be coarser layers through which water can move more rapidly and in larger quantities than it can through the material as a whole. Bedrock may be impermeable itself, but water moves through it in fractures and other such openings called secondary porosity. Groundwater flow is not so generalized in this material where the flow paths are more widely spaced. In addition there are areas within rock formations where fractures are concentrated or are more open so that water can move more readily through these areas. It is this type of situation that has supported the notion of underground streams.
Groundwater may also occur under confined conditions. Groundwater that is confined is isolated from the atmosphere at the point of discharge by aquicludes. The confined aquifer generally has higher pressures than atmospheric acting on it causing the water in a well drilled into the formation to rise above the levy of the formation. *Artesian* is equivalent to confined. It can refer to either the water-bearing material, as in confined aquifer, or to the water confined in the material, as in artesian ground water. The water in a confined material also may be referred to as occurring under confined conditions or artesian conditions. Confined water is held in the water-bearing material by an overlying material of low permeability called the confining layer. Confined water will rise in a well to a level above the top of the water-being material, defining the potentiometric surface at that point. If the potentiometric surface is above the land surface, the well will be a flowing well.

An aquifer performs two important functions—storage and transmission of water. The water in the pore spaces is constantly moving at rates ranging from feet per day to feet per year. The shape, size, volume, and connectivity of the pores and openings affect the ability of the formation to store and transmit water.

Two properties of an aquifer that affect its ability to store water are porosity and specific yield. The porosity is defined as the ratio of the volume of the pore space to the volume of the geologic material. It is expressed quantitatively as the ratio of void space to the total volume of porous material. It is stated as either a decimal fraction or as a percentage and is dimensionless. For example, if 1 ft$^3$ of sand contains 0.25 ft$^3$ of open space or pores, its porosity would be 25%. Primary porosity refers to the original interstices created when a material, such as rock or soil, was formed. Typically, primary porosity is the pore space between grains, pebbles or crystals. Secondary porosity refers to interstices created after a material was formed. Examples are fractures (joints and faults) openings along bedding planes, solution cavities, cleavage, and schistosity. Secondary porosity is the dominant form in consolidated materials such as well cemented and strongly indurated sedimentary rocks and in most and metamorphic or crystalline rocks.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>clay</td>
<td>17-96</td>
</tr>
<tr>
<td>uniform inorganic silt</td>
<td>29-52</td>
</tr>
<tr>
<td>silty sand</td>
<td>23-47</td>
</tr>
<tr>
<td>clean uniform sand</td>
<td>29-50</td>
</tr>
<tr>
<td>fine to coarse sand</td>
<td>17-49</td>
</tr>
<tr>
<td>silty sand &amp; gravel</td>
<td>12-46</td>
</tr>
</tbody>
</table>

Table 2.1 Typical Porosities of Geologic Materials

Table 2.1 provides typical values for common geologic materials. Although the porosity represents the volume of water an aquifer can hold, it does not represent how much water the aquifer will yield.

An example is needed to explain this concept. When water is drained from a saturated sponge by gravity, the sponge releases only a small portion of the total volume of water stored in its pores or openings. This is true of an aquifer as well. The quantity of water that a unit volume of unconfined aquifer yields up to gravity is called its *specific yield*. 
The amount of water that a unit volume of aquifer retains after gravity drainage is called its specific retention. The porosity of an aquifer is the sum of the specific yield and the specific retention. Specific yields are not determined for confined aquifers because the water is not completely removed from the pores during pumping.

### 2.1. Permeability

The transmission function of an aquifer is related to its ability to conduct water. The property of an aquifer directly related to this ability is called its coefficient of permeability or hydraulic conductivity. The permeability of an aquifer is governed by the size, shape, and connectivity of the pores, as well as the properties of the fluid moving through the pores. If the pores are small and not well connected, the ability of a fluid to flow through the aquifer will be low and the aquifer will have a low permeability. Typical values of the coefficient of permeability are shown in Figure 2.3.
These values are used to predict how much fluid will flow in a given time through a cross section of aquifer under a specified hydraulic gradient. The gradient is related to how much pressure is available to cause the water to flow in the aquifer. The higher the gradient, the more water that will flow through the aquifer. According to D'Arcy (1856), if the gradient is doubled, then the amount of water that will flow will be doubled. The D'Arcy equation used to mathematically describe D'Arcy's law is shown in equation 2.1.

\[ q = kiA \]  

(2.1)

where \( q \) = discharge (volume/time), \( k \) = coefficient of permeability (length/time), \( i \) = gradient (length/length), and \( A \) = area through which fluid is flowing (length^2).

### 2.2. Transmissivity

The coefficient of permeability times the aquifer thickness equals the transmissivity. This value describes the rate of flow through a vertical section of a aquifer under a unit gradient. The transmissivity is obtained by pumping tests, by laboratory tests, or by estimating the permeability from grain size measurements. Of these methods, the pumping test proves to be the most accurate.

### 2.3. Groundwater Flow Velocities

The magnitude of groundwater flow velocities is of little interest to persons primarily concerned with water yields from a well. However, with the advent of groundwater contamination, the ability to assess
the velocity of a contact moving in the ground has become of vital importance. From D'Arcy's law, equation 2.2 can be derived.

\[ v = \frac{ki}{\eta} \]  

where \( v \) = velocity of flow through the pores (length/time), \( k \) = coefficient of permeability (length/time), \( i \) = gradient (length/length), and \( \eta \) = porosity. Frequently, tracers such as dyes or salts are used to physically measure this velocity.

### 2.4. Collection of Hydrogeologic Data

Hydrogeologic data are applicable to a variety of problems both directly and indirectly affecting the success of any project. Subsurface water can affect the stability of structures, the costs of construction, the costs of maintenance, and the effects of structures on neighboring properties. To better understand groundwater and its movements the devices used to determine groundwater movement must be known.

#### 2.4.1. Observation Wells

An observation well is a hole that has been bored into the ground to some depth into the saturated zone, and fitted with a casing or a well point in order to maintain an open hole over a period of time. Wells may be drilled purely as observation wells; however, in common practice test borings are connected to observation wells. Existing water wells in the area can also be used.

Observation wells are most often used to measure water levels. These measurements may be made periodically by hand or automatically by a continuous recorder. A common hand instrument is the steel tape. A second hand instrument is a simple, mechanical sounding device attached to a surveyor's tape. The device could be a 4-inch length of 0.5-inch diameter tubing, capped at one end and open at the other. The capped end is attached to the tape by means of a swivel clip. As the tape with the sounding device is lowered into the observation well, a distinctive sound is heard when the open end of the device contacts the water surface. A third hand instrument is the electric probe, which consists of two wires and an ammeter that registers a current when the circuit is closed by the ends of the wires being immersed in the water. This instrument can be used with an accuracy equivalent to the steel tape, and it is more convenient than the tape when water depths exceed 100 ft.

Observation wells are also used to measure the water-bearing characteristics of the materials that they penetrate. Borehole permeability tests are conducted during drilling of the observation well as the hole is advanced. These tests may also be conducted after the boring is completed but before the well is installed. After the observation well is completed, pumping tests can be conducted. The observation well may be used either as a pumping well, for water level measurements during pumping of another well, or for both purposes alternately.

Finally, an observation well may be used to obtain samples of water for chemical analysis to be used in water quality studies. Water samples should be as representative as possible of water as it occurs in the water-bearing material of interest. The chemistry of the water standing in a well will change quite rapidly due to reduced pressure in the well, greater exposure to air, contact with casing and screening materials, and other factors. Therefore, water should be removed from an observation well prior to sampling in order to remove any stagnant or unrepresentative water.
Some judgment is involved in how long to pump a well or otherwise remove water, before sampling, but a widely used standard is to remove an amount of water equal to at least degree times the volume of water standing in the well. Various conditions frequency make it impossible or impractical to purge a well to the desired extent. The extreme case is when a very low-yielding material is being investigated. Then it may be difficult to obtain even enough water at a single sampling to perform the desired analyses. ID any case when a sample is obtained, the duration and rate of water removal prior to sampling should be recorded along with all other conditions of the well and the water, such as whether or not the well is actively used and last usage, depth to water before and after purging and sampling, depth of pump intake or the depth to which other sampling device was lowered, clarity of the water before and after purging and sampling, water temperature, and so on. Water samples should be analyzed as soon after sampling as possible.

2.4.2. Piezometers

A piezometer is a specialized type of observation well designed to determine pore pressure in soil, rock, or other porous material. The piezometer differs from the general observation well in that it is open only to a particular point in the material so that the water level in the piezometer indicates the hydraulic pressure at that point. A general observation well on the other hand is usually open to some thickness of the porous material and is indicative of the average potential in the material over that interval. Pore pressure is determined by subtracting the elevation head (the distance of the point of measurement above some arbitrary datum) from the hydraulic pressure (the height of the potentiometric surface above the same arbitrary datum). The potentiometric surface can be measured in an adjacent observation well or in a second piezometer at the water surface.

![Diagram of a piezometer installation](image)

Figure 2.4. Typical Piezometer Installation Detail

A type of piezometer installation is shown in Figure 2.4. A piezometer may consist of a pipe or casing that is drilled or driven to the desired depth of measurement. With the screened section only at the bottom, water can enter only at the depth of interest and will rise in the pipe in accordance with the hydraulic pressure at that depth. More sophisticated types of piezometers consist of a porous tip sealed into a soil layer and connected to the surface by fluid-filled tubes. Several of these devices may be placed at various depths in one boring. For more accurate leadings, a mechanical or electrical pressure
transducer is placed in the porous tip. This type of piezometer will only measure pore pressures in the saturated zone.

2.4.3. Potentiometric Surface

Potentiometric surface is an imaginary surface connecting points to which water would rise in tightly cased wells from a given point in an aquifer. Potentiometric surface replaces the older term piezometric surface.

A basic objective of groundwater analysis is to define the potentiometric surface. This is done by plotting water elevations from observation well data, and drawing lines of equal elevation, which are for practical purposes, equipotential lines. A minimum of three points of elevation is required to define a plane, but this will yield only the roughest approximation of the potentiometric surface, which is normally an irregular curved surface. The water table is the Potentiometric surface in an unconfined water-bearing material. It usually more or less reflects the surface topography, whereas the potentiometric surface in a confined material may have little or no resemblance to surface topography. Thus, many elevation points (observation wells) are desirable to clearly define the potentiometric surfaces.

The potentiometric surface map shows where recharge and discharge occur, and the directions of groundwater flow. Water flow is at right angles to the equipotential lines, from areas of high potential to areas of low potential.

Water levels may vary with time and in venous cycles. Thus, it is important to obtain water-level measurements in all observation wells as close to the same time as possible.

CHAPTER 3.

WELL HYDRAULICS

3.1. Definition of Terms

It is important to understand clearly the meaning of common terms related to pumping wells. Definitions are presented below, and several terms are defined diagrammatically in Figure 3.1.
3.1.1. Static Water Level

This is the level at which water stands in a well or unconfined aquifer when no water is being removed from the aquifer either by pumping or free flow. It is generally expressed as the distance from the ground surface (or from a measuring point near the ground surface) to the water level in the well. For example, when the static water level in a well is 15 ft, it means that water stands 15 ft below the measuring point when there is no pumping. For an artesian well which flows at the ground surface, the static water level is expressed as a height above the ground surface. When artesian flow is stopped or contained at the ground surface, the pressure developed is referred to as the shut-in head. If the well has a shut-in head of 3 psi at the surface, it means that the confining pressure will cause the water to rise 7 ft in a pipe extending above the ground surface.

3.1.2. Pumping Water Level

This is the level at which water stands in a well when pumping is in progress. In the case of an artesian well, it is the above ground level at which water is flowing from the well. The pumping water level is also called the dynamic water level as measured in the well.

3.1.3. Drawdown
Drawdown is the difference, measured in feet or meters, between the water table or potentiometric surface and the pumping water level. This difference represents the head of water (force) that causes water to flow through an aquifer toward a well at the rate that water is being withdrawn from the well. In the unconfined case, the head is represented graphically by the actual water level at a point along the drawdown curve. In confined conditions, the drawdown curve represents the pressure head at that point. To differentiate these two types of drawdown, all diagrams in this manual show the water table for unconfined conditions as a solid line and the potentiometric surface for confined conditions as a dashed line.

3.1.4. Residual Drawdown

After pumping is stopped the water levy rises and approaches the static water level observed before pumping began. During water level recovery, the distance between the water level and the initial static water level is called residual drawdown.

3.1.5. Well Yield

Yield is the volume of water per unit of time discharged from a well, either by pumping or free flow. It is measured commonly as a pumping rate in gallons per minute or cubic meters per day.

3.1.6. Specific Capacity

Specific capacity of a well is its yield per unit of drawdown, usually expressed as gallons of water per minute per foot (gpm/ft) of drawdown or cubic meters per day per meter of drawdown, after a given time has elapsed, usually 24 hours. Dividing the yield of a well by the drawdown, when each is measured at the same time, gives the specific capacity. For instance, if the pumping rate is 1,000 gpm and the drawdown is 30 ft. the specific capacity of the well is about 33.3 gpm per ft of drawdown at the time the measurements were taken. Specific capacity generally varies with duration of pumping; as pumping time increases, specific capacity decreases. Also, specific capacity decreases as discharge increases in the same well. The reasons for decreasing specific capacity are discussed later in this chapter.

Static water level pumping water level, drawdown, and residual drawdown apply similarly to a pumped well or other nearby wells and observation wells. For example, if the water level in an observation well located 80 ft from a pumping well dropped 3 ft as a result of the pumping, this lowering in the observation well is called its drawdown.

3.2. Nature of Converging Flow

The water level in the vicinity of a pumped well under unconfined conditions is lowered when pumping begins, with the greatest drawdown occurring in the well. As the pomp removes water, an area of low pressure develops near the well bore. Because the water level is lower in a pumped well than at any place in the water-bearing formation surrounding it, water moves from the formation into the well to replace water being withdrawn by the pump. The pressure (force) that drives the water toward the well is called the head, which is the difference between the water level inside the well and the water level at any place outside the well. At some distance from the well a point is reached where the water level is essentially unaffected. This distance varies for different wells. It also varies for the same well depending on both the pumping rate and the length of time the well is pumped.
In confined formations, the saturated thickness of the aquifer is generally not reduced during pumping. Hydrostatic pressure, however, is reduced in the aquifer, and the pressure drop is greatest at the well bore. The pressure drop is directly analogous to the dewatering effect in unconfined aquifers.

During pumping, water flows toward the well from every direction. As the water moves closer to the well, it moves through imaginary cylindrical sections that are successively smaller in area. Thus, as the water approaches the well, its velocity increases. In Figure 3.2, A₁ represents the area of a cylindrical surface 100 ft from the center of the well and A₂ represents the area of a similar surface 50 ft from the well. Because A₁ is twice A₂ and

the same quantity of water flows toward the pumped well through both cylinders, the velocity V₂ must be twice V₁.

Darcy's law indicates that the velocity of flow through porous media varies directly with the hydraulic gradient. As the hydraulic gradient increases, velocity increases as flow converges toward a well. As a result, the lowered water surface develops a continually steeper slope toward the well. The form of this surface resembles a cone and is called the cone of depression. When pumped, all wells are surrounded by a cone of depression. Each cone differs in size and shape depending upon the pumping rate, pumping duration, aquifer characteristics, slope of the water table, and recharge within the cone of depression of the well.

Figure 3.3 shows two cones of depression around pumped wells that illustrate how transmissivity of an aquifer affects the shape of the cone. In a formation with low transmissivity, the cone is deep with steep sides and has a smog radius. In a formation with high transmissivity, the cone is shallow with flat sides and has a large radius. The explanation for these different cone shapes is clear, for greater hydraulic head
(feet of head) is required to move water through a less permeable formation than through a more permeable formation.

Figure 3.4 shows the levels at which water would be found in observation wells drilled at various distances from a pumped well. Only one side is shown; the other side is similar. This curve is called the drawdown curve and represents the lower limits of the cone of depression. In an unconfined aquifer, it represents the level to which the formation remains saturated. In a confined aquifer, it represents the hydrostatic pressure in the aquifer. Drawdown at any given point is the difference between the water level indicated by the curve and the static water level.

Head loss is a term used to describe the difference in head (pressure) that is required to cause flow from one point to another in an aquifer; it is a measure of the force required to overcome resistance to flow.
The head losses from point to point along the pumping water level curve in Figure 3.4 are the differences in drawdown between these points.

Suppose, for example, that a well is pumped at a constant rate of 600 gpm. At a distance of 28 ft from the well, the drawdown is about 5 ft. This indicates that 5 ft of head are required to force 600 gpm of water through the formation from the outer limit of the cone of depression to within 28 ft of the well. Another 5 ft of head is required to move the same volume of water from 28 ft to within 14 ft of the well. At this point, the drawdown is about 10 ft. The remainder of the total drawdown or head loss is used in pushing the water through the last 14 ft of the formation and through the well screen. The total drawdown of 20 ft in the well is the head in feet required to move 600 gpm through the aquifer (within the cone of depression of the well) and into the well. This example shows that more head is expended for a given horizontal distance as the flow converges toward the well bore. The area through which the water moves decreases steadily while the velocity increases, resulting in increasing head loss along the flow path toward the well.

Before proceeding to the equations describing groundwater flow, three important terms must be defined. Each of these terms describes a characteristic of the aquifer that can be determined by pumping

3.2.1. Radius of Influence

Radius of influence, R, is the horizontal distance from the center of a well to the limit of the cone of depression. It is larger for cones of depression in confined aquifers than for those in unconfined aquifers. The reason for this difference will become clear later in this chapter.

3.2.2. Coefficient of Storage

Coefficient of storage, S, of an aquifer represents the volume of water released from storage, or taken into storage, per unit of aquifer storage area per unit change in head. In unconfined aquifers, S is the same as the specific yield of the aquifer. In confined aquifers, S is the result of compression of the aquifer and expansion of the confined water when the head (pressure) is reduced during pumping. The coefficient of storage is dimensionless.

Values of S for unconfined aquifers range from 0.01 to 0.3; values for confined aquifers range from 10^{-5} to 10^{-3}.

3.2.3. Coefficient of Transmissivity

Coefficient of transmissivity, T, of an aquifer is the rate at which water flows through a vertical strip of the aquifer 1 ft or 1 m wide and extending through the full saturated thickness, under a hydraulic gradient of 1 (100 percent). Figure 3.5 illustrates the concepts of hydraulic conductivity and transmissivity. Values of T range from less than 1,000 to more than 1 million gpd/ft. If an aquifer has a transmissivity of less than 1,000 gpd/ft, it can supply only enough water for domestic wells or other low-yield uses. When the transmissivity is 10,000 gpd/ft or more, well yields can be adequate for industrial, municipal, or irrigation purposes.
Figure 3.5. Illustration of the coefficients of hydraulic conductivity and transmissivity. Hydraulic conductivity multiplied by the aquifer thickness equals the coefficient of transmissivity.
The transmissivity and storage coefficients are especially important because they define the hydraulic characteristics of a water-bearing formation. The coefficient of transmissivity indicates how much water will move through the formation, and the coefficient of storage indicates how much can be removed by pumping or draining. If these two coefficients can be determined for a particular aquifer, predictions of great significance can usually be made. Some of these are:

1. Drawdown in the aquifer at various distances from a pumped well.
2. Drawdown in a well at any time after pumping starts.
3. How multiple wells in a small area will affect one another.
4. Efficiency of the intake portion of the well.
5. Drawdown in the aquifer at various pumping rates.

3.3. Cone of Depression
When water is pumped from a well, the initial discharge is derived from casing storage and aquifer storage immediately surrounding the well (Figure 3.6). As pumping continues, more water must be derived from aquifer storage at greater distances from the well bore. This means that the cone of depression must expand. The radius of influence of the well increases as the cone expands. Drawdown at any point also increases as the cone deepens to provide the additional head required to move the water from greater distances. The cone expands and deepens more slowly with time, however, because an increasing volume of stored water is available with each additional foot of horizontal expansion.

Figure 3.7 illustrates how the cone of depression expands during equal intervals of time. Assume that after 10 hours of pumping the radius of the cone is 400 ft and its depth is 6 ft at the well bore. At the end of 20 hours, the cone's radius has expanded to 570 ft and its depth has increased to 6.3 ft. In the second 10 hours, the cone has only extended outward an additional 170 ft and deepened by an additional 0.3 ft. An additional radial expansion of only 130 ft and an increase in depth of only 0.2 ft occurs in the next 10 hours. Calculations of the volume of each of the cones would show that cone 2 has twice the volume of cone 1, and cone 3 has three times the volume of cone 1. This occurs because, at a constant pumping rate, the same volume of water is discharged from the well during each 10-hour interval. Thus, the increase in volume of the cone of depression is constant over time if the well is being pumped at a constant rate and the aquifer is homogeneous.

It is evident from this example that after some hours deepening or expansion of the cone during short intervals of pumping is barely discernible. This often leads observers to conclude that the cone has stabilized and will not expand or deepen as pumping continues. The cone of depression will continue to enlarge, however, until one or more of the following conditions is met:

1. It intercepts enough of the flow in the aquifer to equal the pumping rate.

2. It intercepts a body of surface water from which enough additional water will enter the aquifer to equal the pumping rate when combined with all the flow toward the well.

3. Enough vertical recharge from precipitation occurs within the radius of influence to equal the pumping rate.
4. Sufficient leakage occurs through overlying or underlying formations to equal the pumping rate.

When the cone has stopped expanding because of one or more of the above conditions, equilibrium exists. There is no further drawdown with continued pumping. In some wells, equilibrium occurs within a few hours after pumping begins; in others, it never occurs even though the pumping period may be extended for years.

CHAPTER 4

WELL DRILLING METHODS

Various well drilling methods have developed because geologic conditions range from hard rock such as granite and dolomite to completely unconsolidated sediments such as alluvial sand and gravel. Particular drilling methods have become dominant in certain areas because they are most effective in penetrating the local aquifers and thus offer cost advantages. In many cases, however, the drilling contractor may vary the usual drilling procedure depending on the depth and diameter of the well, type of formation to be penetrated, sanitation requirements, and principal use of the well. It is obvious, then, that no single drilling method is best for all geologic conditions and well installations. In most cases, the drilling contractor is best qualified to select the particular drilling procedure for a given set of construction parameters. Successful drilling is both an art developed from long experience and the application of good engineering practices.

Well construction usually comprises four or five distinct operations: drilling, installing the casing, placing a well screen and filter pack, grouting to provide sanitary protection, and developing the well. Two or more of these operations may be carried out simultaneously, depending on the drilling method used. For example, when drilling into an unconsolidated formation by the cable tool or drill through casing driver methods, the casing is installed as drilling proceeds. When a well point (screen) is driven, three operations are performed simultaneously: the borehole is opened, the casing installed, and the well screen set.

Well drilling and installation methods are so numerous that only the basic principles and some of their applications can be described in this chapter. The practical limits of major drilling methods are presented for various geologic conditions.

4.1. CABLE TOOL METHOD

Developed by the Chinese, the cable tool percussion method was the earliest drilling method and has been in continuous use for about 4,000 years. Using tools constructed of bamboo, the early Chinese could drill wells to a depth of 3,000 ft, although construction sometimes took two to three generations. Cable tool drilling machines, also called percussion or "spudder" rigs, operate by repeatedly lifting and dropping a heavy string of drilling tools into the borehole. The drill bit breaks or crushes consolidated rock into small fragments, whereas the bit primarily loosens the material when drilling in unconsolidated formations. In both instances, the reciprocating action of the tools mixes the crushed or loosened particles with water to form a slurry or sludge at the bottom of the borehole. If little or no water is present in the penetrated formation, water is added to form a slurry. Slurry accumulation increases as drilling proceeds and eventually it reduces the impact of the tools. When the penetration rate becomes unacceptable, slurry is removed at intervals from the borehole by a sand pump or bailer.
A full string of cable tool drilling equipment consists of five components: drill bit, drill stem, drilling jars, swivel socket, and cable. Each component has an important function in the drilling process. The cable tool bit is usually massive and heavy so as to crush and mix all types of earth materials. The drill stem gives additional weight to the bit, and its length helps to maintain a straight hole when drilling in hard rock. (Please scroll to next page for graphic)
Figure 4.1. Engineering drawing of a Bucyrus-Erie Model 22-W shows how the drill line is reeved in a typical cable tool rig. The spudding action is imparted to the drill line by the vertical motion of the walking beam. The shock absorber mounted beneath the crown block helps control the impact of the bit on the rock. (Bucyrus-Erie Company)
Drilling jars consist of a pair of linked, heat-treated steel bars. When the bit is stuck, it can be freed most of the time by upward blows of the free-sliding jars. This is the primary function of the drilling jars; except in unusual circumstances, they serve no purpose in the drilling operation itself. The stroke of the drilling jars is 9 to 18 in and distinguishes them from fishing jars which have a stroke of 18 to 36 in or longer.

The swivel socket connects the stung of tools to the cable; in addition, the weight of the socket supplies part of the weight of the drill tools. It also supplies part of the upward energy to the jars when their use becomes necessary. The socket transmits the rotation of the cable to the tool string and bit so that new rock is cut on each downstroke, thereby assuring that a round, straight hole will be cut. The elements of the tool string are screwed together with right-hand threaded tool joints of standard API (American Petroleum Institute) design and dimension.

The wire cable that carries and rotates the drilling tool is called the drill line. It is a 5/8-to 1 in left-hand lay cable that twists the tool joint on each upstroke to prevent it from unscrewing. The drill line is reeved over a crown sheave at the top of the mast, down to the spudding sheave on the walking beam, to the heel sheave, and then to the working-line side of the bull reel (Figure 4.1). Bull reels are generally set up with a separator on the drum to provide a working-line side and a storage-line side.

Bailers used to remove the mud or rock slurry consist of a pipe with a check valve at the bottom. The valve may be either a flat pattern or a ball-and-tongue pattern called a dart valve. A bail handle at the top of this tool attaches to a cable called the sand line. The sand line is threaded over a separate sheave at the top of the mast and down to the sand-line reel. The diameter of the sand line can vary according to the anticipated loads.

Another type of bailer is called the sand pump or suction bailer. This bailer is fitted with a plunger so that an upward pull on the plunger tends to produce a vacuum that opens the valve and sucks sand or slurried cuttings into the tubing. The sand pump can have a bit bottom, but more often in water well drilling it has a flat bottom with a flap-type valve. Some sand pump bailers have a latch bottom for slurry release. Most sand pumps are either 10 or 20 ft long.

The characteristic up and down drilling action of a cable-tool machine is imparted to the drill line and dolling tools by the walking beam. The walking beam pivots at one end while its outer end, which carries a sheave for the drill line, is moved up and down by a single or double pitman connected to a crank shaft. The vertical stroke of the walking beam, and thus the drill tools, can be varied by adjusting the position of the pitman pin on the bull gear and the pitman connection to the walking beam. The number of strokes per minute can be varied by changing the speed of the drive shaft. The bull gear is driven by a pinion mounted on a clutch. This clutch, the friction drive for the sand line (on smaller cable tool rigs only), and the drive pinion for the drill-line reel are all mounted on the same drive shaft assembly.

Another drum, called a casing reel, is frequently added to the basic machine assembly. The casing reel is capable of exerting a powerful pull on a third cable, the casing line. This cable is used for handling pipe, tools, and pumps, or other heavy hoisting. It may be used to pull a string of casing when the cable is reeved with blocks to make two-, three-, or four-part lines.

Another commonly used auxiliary hoisting device on a cable tool machine is called a cathead. Use of this drum requires that a heavy line of manila rope be carried on a separate sheave at the top of the derrick. This line may be used for handling light loads and alternately lifting and dropping tools such as a drive block or bumper which are used to drive or lift casing.
Every cable tool machine has certain interdependent limits on borehole depth and diameter. If a hole is relatively small in diameter, it may be drilled to relatively great depth. In large diameter holes, the weight of the drill string and cable may become so excessive that the machine cannot function. Collapsing formations may further limit the effective depth for large-diameter casing, because considerable friction develops between the casing and borehole wall while the casing is being driven. In many cases, the casing size is progressively decreased as the hole is deepened, thereby reducing friction and also the weight of the drilling tools. Friction between the borehole wall and casing can be reduced by the addition of a drilling fluid slurry around the outside of the casing during driving. This small amount of slurry will also decrease the energy required for pulling back casing to expose screens set within the casing. In water well drilling, the depth capability for cable tool rigs ranges from 300 to 5,000 ft.

The drilling motion of the cable tool machine must be synchronized with the gravity fall of the tools for effective penetration. Several factors (thickness of the slurry in the borehole, whip in the cable, hole alignment, and rocks protruding in the borehole) may interfere with the free gravity fall, and the driller must adjust the motion and speed of the machine to the vertical movement of the tools. Effective drilling action is obtained when the engine speed is synchronized with the fall of the tools and the stretch of the cable, while paying out the correct amount of cable to maintain proper feed of the bit. The bit should strike the bottom of the hole at the extreme (elastic) limit of the cable and immediately snap upward so that a sharp blow is given to the earth material by the bit. This requires some resilience and elasticity in the cable and certain parts of the rig mechanism. An elastic snubber or shock absorber is usually installed in the mounting of the drill-line crown sheave to provide part of the resilience in the system. The shock absorber compresses as the walking beam completes its upstroke and starts its pull on the cable. Cable tension then reaches its maximum, because the tools are still moving downward. The shock absorbers rebound helps to lift the tools sharply after they strike bottom. The objective is to give the tools that peculiar whip at the end of the stroke which is essential to rapid drilling. At the surface, the cable will appear to be constantly in tension. When properly done, this technique conserves power and increases drilling speed. The shock absorber also dampens the vibration that occurs when the drill bit strikes the bottom of the hole; it protects the derrick and the rest of the machine from severe shock stresses.

The cable tool method has survived for thousands of years because it is reliable for a wide variety of geologic conditions. It may be the best, and in some cases the only, method to use in coarse glacial till, boulder deposits, or rock strata that are highly disturbed, broken, fissured, or cavernous. In situations where the aquifers are thin and yields are low, the cable tool operation permits identification of zones that might be overlooked in other drilling methods. The cable tool method offers the following advantages:

1. Rigs are relatively inexpensive.
2. Rigs are simple in design and require little sophisticated maintenance.
3. Machines have low energy requirements.
4. Borehole is stabilized during the entire drilling operation.
5. Recovery of samples is possible from every depth unless heaving conditions occur.
6. Wells can be drilled in areas where little make-up water exists.
7. Wells can be constructed with little chance of contamination.
8. The driller maintains intimate contact with the drilling process and the materials encountered by keeping a hand on the drilling cable.
9. Because of size, machines can be operated in more rugged, inaccessible terrain or in other areas where space is limited.
10. Rigs can be operated in all temperature regimes.
11. Wells can be drilled in formations where lost circulation is a problem.
12. Wells can be bailed at any time to determine the approximate yield at that depth.

Some disadvantages of the cable tool method include the following:

1. Penetration rates are relatively slow.
2. Casing costs are usually higher because heavier wall or larger diameter casing may be required.
3. It may be difficult to pull back long strings of casing in some geologic conditions, unless special equipment is available.

4.2 DIRECT ROTARY DRILLING
The direct rotary drilling method was developed to increase drilling speeds and to reach greater depths in most formations. The borehole is drilled by rotating a bit, and cuttings are removed by continuous circulation of a drilling fluid as the bit penetrates the formation. The bit is attached to the lower end of a string of drill pipe, which transmits the rotating action from the rig to the bit. In the direct rotary system, drilling fluid is pumped down through the drill pipe and out through the ports or jets in the bit, the fluid then flows upward in the annular space between the hole and drill pipe, carrying the cuttings in suspension to the surface. At the surface, the fluid is channeled into a settling pit or pits where most of the cuttings drop out. Clean fluid is then picked up by the pump at the far end of the pit or from the second pit and is recirculated down the hole. For relatively shallow wells, 150- to 500-gal portable pits may be used; much larger portable pits, 10,000 to 12,000 gal, are used for deeper wells. Mud pits may also be excavated for temporary use during drilling and then backfilled after completion of the well.

Before 1920, the type of rotary drill used in water well drilling was commonly called a whirler. This equipment used the well casing itself as the drill pipe. The lower end of the pipe was fitted with a serrated cutting shoe with an outside diameter a little larger than the drill pipe couplings. The sawteeth of the shoe cut and loosened the materials as the pipe was rotated. Water was pumped under pressure through the pipe to lift the cuttings to the surface. Native clays and silt were depended upon to seal the borehole wall to maintain circulation; prepared drilling fluids were not used. The method was suitable for drilling only relatively small-diameter, shallow wells in unconsolidated formations that did not contain cobbles or boulders.

In the 1930's, shot-hole rotary drills, used for seismograph work in oil exploration, were successfully adapted for drilling large diameter water wells. Shot-hole machines, however, could not drill the large diameter holes necessary for water well work because the mud pump and drill pipe were generally too small to circulate enough drilling fluid to efficiently drill even an 8-in well. In time, truck-mounted portable rigs for drilling large diameter water wells were developed from oil field exploration technology.

The components of the rotary drilling machine are designed to serve two functions simultaneously: operation of the bit and continuous circulation of the drilling fluid. Both are indispensable in cutting and maintaining the borehole. For economic and efficient operation, rotary drillers must acquire considerable knowledge concerning these factors and how they relate to various formation conditions.

In direct circulation rotary drilling for water wells, two general types of bits are used—the drag bit (fishtail, three, and six-way designs) and the roller cone bit, usually called a rock bit. Drag bits have short blades, each forged to a cutting edge and faced with durable metal. Short nozzles direct jets of drilling fluid down the faces of the blades to clean and cool them. Drag bits have a shearing action and cut rapidly in sands, clays, and some soft rock formations, but they do not work well in coarse gravel or hard-rock formations.

Roller (cone) bits exert a crushing and chipping action, making it possible to cut hard formations. The rollers, or cutters, are made with either hardened steel teeth or tungsten carbide inserts of varied shape, length, and spacing, designed so that each tooth applies pressure at a different point on the bottom of the hole as the cones rotate. The teeth of adjacent cones intermesh so that self-cleaning occurs. Long, widely spaced teeth are used in bits designed to cut soft clay formations, whereas shorter, closer spaced teeth are used for denser formations. Some roller bits are made with carbide buttons for particularly dense and abrasive formations such as dolomite, granite, chert, basalt, and quartzite.
The tricone bit, used as an all-purpose bit in every type of formation, has conically shaped rollers on spindles and bearings set at an angle to the axis of the bit. Another design has four rollers; two are set at an angle and two are normal to the vertical axis of the bit. The cutting surfaces of all roller bits are flushed by jets of drilling fluid directed from the inside (center) of the bit. The jets can be sized so as to maximize the cutting action of the bit. The jets are also effective in breaking up or washing away soft formation materials.

The bit is attached to the lower end of the drill pipe, which resembles a long tubular shaft. The drill string usually consists of four parts: the bit, one or more drill collars or stabilizers, one or more lengths of drill pipe, and, in table-drive machines, the kelly. Selection of the bottomhole assembly will depend on the physical conditions of the geologic materials. These include dip of the formation, presence of faults or fractures, and drillability of the formation.

Each drill collar is a heavy-walled length of drill pipe; one or more drill collars are used to add weight to the lower end of the drill-stem assembly. The concentration of weight just above the bit helps to keep the hole straight, and provides sufficient weight for the bit to maintain the proper penetration rate. Drill collars fitted with stabilizer bars or rollers are even more effective in drilling straight boreholes.

![Diagram of drill pipe with tool-joint pin and box-end fitting.](image)

*Figure 4.3. Drill pipe is heavy-walled seamless tubing with tool-joint pin and box-end fittings.*

Stabilizers are an important component of the bottom-hole tools. To be effective in maintaining straight holes in soft formations, the stabilizer must have large wall contact. Increased contact can be achieved by using stabilizers with longer and wider blades, or by using longer stabilizers. The flow of drilling fluid upward around the stabilizer must not be restricted too much, however, because cuttings may pack around the stabilizer. This leads to sticking and a possible loss of circulation if back pressure builds up. Weakening of the formation structure can also result from the pressure increase. Accumulation of
cuttings around the stabilizer may also cause local zones of erosion in the borehole wall. In relatively hard formations, the stabilizer can perform satisfactorily with less wall contact.

Drill pipe is seamless tubing manufactured in joints that are usually 5.0 to 20.0 ft long, although other lengths are available. Each joint is equipped with a tool joint pin on one end and a tool joint box on the other (Figure 4.3). Outside diameters of drill pipe used for direct rotary drilling generally range from 2 to 6 in. High circulation rates for drilling fluids in water well drilling require that the drill pipe diameter be adequate to hold friction loss in the pipe to an acceptable level so as to reduce the power required for the pump. For efficient operation, the outside diameter of the tool joint should be about two-thirds the borehole diameter; this ratio may be impractical, however, for holes larger than 10 in.

In table-drive machines, the kelly constitutes the uppermost section of the drill string column. It passes through and engages in the opening in the rotary table, which is driven by hydraulic or mechanical means. The outer shape of the kelly may be square or hexagonal, or round with lengthwise grooves or flutes cut into the outside wall. Made about 3 ft longer than one joint of drill pipe, the kelly has an inside bore that is usually smaller than that of the drill pipe because of the heavy wall thickness required. The square, hexagonal, or grooved circular section of the kelly works up and down through drive bushings in the rotary table. With the bushings properly in place around the kelly, the entire drill stem and bit are forced to turn with the rotary table. While rotating, the kelly slips down through the drive bushings to feed the bit downward as the hole is drilled. The upper end of the kelly connects to a swivel (by a left-hand threaded joint) that is suspended from a traveling block in the derrick. A heavy thrust bearing between the two parts of the swivel carries the entire weight of the drill string while allowing the drill pipe to rotate freely.

Some rotary drilling machines use a towhead drive to rotate the drill string. In this system, the rotational unit moves up and down the mast; energy is obtained from a hydraulic transmission unit powered by a motor-driven pump.

In both the rotary table and top-head drive mechanisms, the driller can determine the rotation speed depending on the resistance of the formation and the rate of penetration. For shallow boreholes of 200 to 400 ft. pull-down pressure may be applied to the bit. Down-hole pressures on the bit can be increased beyond the weight of the drill string by exerting a pull-down force derived from the weight of the drilling rig. The chain assemblies (or cables) on the mast are used to transfer part of the weight of the drilling rig to the drill string. Caution should be used to avoid excessive pull-down pressure (weight) because hole deflection (crooked holes) may result. Rotation speed is adjusted to the pull-down or existing pressures on the bit. In general the higher the pressure on the bit the slower the rotation should be.

Adding drill rods to the drill string or removing rods to change bits or take split-spoon or core samples is a major part of every rotary drilling operation. “Tripping in" and "tripping out" are the terms used to describe the process of running the bit into or pulling the bit from the hole. Most newer drilling rigs have been designed to make this process as fast and automated as possible. With some new machines, it is possible to pull back a 20-ft rod and remove it from the drill string in approximately 30 seconds. In general, top-head drive machines, especially those equipped with carousels (drill rod storage racks mounted on the mast), offer an advantage in rod handling speed, although recent modifications in table-drive machines have enabled this type of rig to match the speed of the top-head drive rotaries.

In top-head drive machines, no kelly is required and therefore the bottom sub of the hydraulic drive motor is connected directly to the drill rod. Additional rods can be taken directly from a carousel by the top-head drive unit. If the machine is equipped with side storage racks, a sand line must be used to raise
the drill rod into position.

Internal pressure created by the drilling fluid can cause a momentary but forceful surge of drilling fluid out of the drill string at the point where the kelly is disconnected from the upper drill rod.

Drillers usually break this joint slowly to allow the pressure to dissipate so that drilling fluid is not expelled violently. Occasionally during the addition of a drill mud, drilling fluid may continue to overflow from the top of the rods. Confining pressures within permeable material in the borehole may be causing this flow, but it is more likely that clay "collars" packed around the drill rods are falling deeper into the borehole, thereby pushing drilling fluid back up the center of the rods.

When circulation of the drilling fluid is interrupted for some reason, to add drill pipe for example, the cuttings being canted by the mud column tend to drop back toward the bottom of the hole. Cuttings can bridge on tool joints and build up on top of the bit if they settle rapidly. Excessive pump pressures may then be required to move these cuttings and resume circulation: if the cuttings cannot be removed, the drill pipe and bit become stuck in the hole (sanded in). Many drilling fluids develop gel strength, that is, the ability to suspend cuttings when flow slows or stops. It may be advisable before adding drill pipe to circulate the fluid for a few minutes without applying bit pressure to clear the hole of most cuttings. This is particularly important for deep holes.

The drilling fluid prevents caving of the borehole because it exerts pressure against the wall. As long as the hydrostatic pressure of the fluid exceeds the earth pressures and any confining pressure in the aquifer, the hole will remain open. The pressure at any depth is equal to the weight of the drilling fluid column above that point.

If caving occurs while drilling, weighting material may be added to increase the drilling fluid weight or special additives may be added to isolate any swelling clays. To prevent excessive intrusion of fine drilling fluid particles into the formation, the drilling fluid weight should be just heavy enough to maintain hole stability. Numerous additives are available for imparting specific properties to drilling fluids. Chapter 5 discusses the various kinds of drilling fluids, with particular reference to their advantages and disadvantages in certain geologic formations.

As drilling progresses, a film of small particles builds up on the wall of the borehole. This flexible lining, which may consist of clay, silt, or colloids, forms when the pressure of the drilling fluid forces smog volumes of water into the formation, leaving the fine, suspended material on the borehole wall. In time, the lining completely covers the wall and holds loose particles or crumbly materials in place. It protects the wall from being eroded by the upward-flowing stream of drilling fluid, and acts to seal the wall and reduce the loss of fluids into surrounding permeable formations. Although the flexible lining effectively controls fluid losses in the borehole, it cannot prevent the hole from collapsing if the hydrostatic pressure created by the drilling fluid is not greater than the pressure exerted by the water in the formation.

The drip bit is cooled and cleaned by the jets of fluid that are directed at relatively high velocity over the cutting faces and body section of the bit. A properly prepared drilling fluid is an excellent lubricant, but the viscosity must be controlled so that the concentration of cuttings does not become excessive.

In direct rotary drilling, water and special viscosity-building additives are usually mixed to produce a drilling fluid. Drilling fluids can be mixed in either a portable pit cantled from site to site or in a pit excavated next to the drilling rig. Cuttings collecting on the bottom of the pit must be removed periodically to maintain the efficiency of the pit. When enough drilling fluid has been mixed and
sufficient time has elapsed to insure complete hydration, it is cad into the hole using a mud pump. The size of the mud pump must be chosen carefully so that the correct uphole velocity can be maintained.

In clay-rich formations, the driller may begin drilling with clean water which quickly mixes with the natural clays in the borehole to form a thin clay slurry. This drilling fluid is used in the upper portion of the borehole, commonly the first 100 to 300 ft. Thereafter, most drillers will mix fluids with additives of either high-quality clays or natural or synthetic polymers so that proper viscosity and hydrostatic pressure can be maintained in the borehole.

Direct rotary drilling, the most common method, offers the following advantages:

1. Penetration is relatively high in all types of materials.
2. Minimal casing is required during the drilling operation.
3. Rig mobilization and demobilization are rapid.
4. Well screens can be set easily as part of the casing installation.

Major disadvantages include the following:

1. Drilling rigs are costly.
2. Drilling rigs require a high level of maintenance.
3. Mobility of the rigs may be limited depending on the slope and condition (wetness) of the land surface.
4. Collection of accurate samples requires special procedures.
5. Use of drilling fluids may cause plugging of certain formations.
6. Rigs cannot be operated economically in extremely cold temperatures.
7. Drilling fluid management requires additional knowledge and eminence.

4.3. REVERSE CIRCULATION ROTARY DRILLING

In direct rotary drilling, the viscosity and uphole velocity of the drilling fluid are the controlling factors in removing cuttings effectively. Unless cuttings can be removed, drilling cannot continue. Because of limitations in pump capacity and therefore effective cuttings removal most direct rotary machines used to drill water wells are limited to boreholes with a minimum diameter of 22 to 24 in. This size may not be sufficient for high capacity wells, especially those that are to be filter packed. Also, as hole diameters increase past 24 in, the rate of penetration by direct rotary machines becomes less satisfactory. To overcome the limitation on hole diameter and drilling rate, reverse circulation machines were designed, originally they were used only in unconsolidated formations. Recently, reverse circulation drilling has been used in soft consolidated rocks such as sandstone and even in hard rocks using both water and air as the drilling fluid.

The design of a reverse circulation rig is essentially the same as that of the direct rotary rig except most pieces of equipment are larger. For example, larger compressors and mud pumps are required because of the larger diameter boreholes. Only table drives are used in reverse circulation drilling because of the large borehole diameter and the torque required to turn the bit.

In reverse circulation rotary drilling, flow of the drilling fluid is reversed when compared with the direct rotary method. The suction end of the centrifugal pump, rather than the discharge end is connected through the swivel to the kelly and drill pipe. The drilling fluid and its load of cuttings move upward inside the drill pipe and are discharged by the pump into the settling pit (Figure 4.4). Centrifugal pumps
with large passageways are often used to pump the drilling fluid because they can handle cuttings without excessive wear on the pump. In operation, however, most of the cuttings do not actually enter the pump but bypass it by means of an eductor system. An uphole velocity of at least 150 ft/min is recommended. The fluid returns to the borehole by gravity flow. It moves down the annular space between the drill pipe and borehole wall to the bottom of the hole, picks up the cuttings, and reenters the drill pipe through ports in the drill bit.

Figure 4.4. In a reverse rotary circulation system, the drilling fluid flows from the mud pit down the borehole outside the drill rods, then passes upward through the bit into the drill rods after entraining the cuttings. After flowing through the swivel and mud pump, it passes into the mud pit where the cuttings settle out.

In the reverse circulation method, the drilling fluid can best be described as muddy water rather than drilling fluid; drilling fluid additives are seldom mixed with the water to make a viscous fluid. Suspended clay and silt that recirculate with the fluid are mostly fine materials picked up from the formations as drilling proceeds. Occasionally, low concentrations of a polymeric drilling fluid additive are used to reduce friction, swelling of water-sensitive clays, and water loss.

To prevent caving of the hole, the fluid level must be kept at ground level at all times, even when drilling is suspended temporarily, to prevent a loss of hydrostatic pressure in the borehole. The hydrostatic pressure of the water column plus the velocity head (inertia of the water moving downward) outside the drill pipe support the borehole wall. Erosion of the wall is usually not a problem because velocity in the annular space is low.

4.3.1. During Drilling

Water infiltrates the permeable formations surrounding the borehole. Some of the fine particles
suspended in the fluid are filtered out on the wall of the hole, resulting in a thin mud deposit that partially clogs the pores and reduces the water loss. A considerable quantity of made-up water is usually required and must be immediately available at all times when drilling in permeable sand and gravel. Under these conditions, water loss can increase suddenly, and if this causes the fluid level in the hole to drop significantly below the ground surface, caving usually results. Water loss can be reduced by nixing clay additives with the fluid, but this is usually avoided unless absolutely necessary. As little as 20 gpm of make-up water is enough in some cases, whereas as much as 1,000 gpm may be needed when drilling through a highly permeable aquifer such as coarse, dry gravel.

The settling pit and water supply pit should hold at least three times the volume of the material to be removed during the drilling operation. The circulation rate for the water used in drilling is commonly 500 gpm or more.

Many reverse rotary drilling rigs are equipped with air compressors to aid in circulating the drilling fluid. When drilling has reached a depth sufficient for proper operation of an air lift within the drill pipe, the mud pump is bypassed. Compressed air is introduced through a 1-1/4 or 1-1/2 plastic or metal air line suspended inside the drill pipe, or through an external air line attached to the outside of the drill pipe. The external air line system may consist of two pipes welded on opposite sides of the drill pipe. The air is injected by means of a manifold into the drill string at the proper depth. In these processes, water is lifted to the surface from the borehole.

Any cobbles or boulders larger than the drill pipe or the openings in the drill bit cannot be brought out in the drilling operation, because most reverse rotary bits cannot break cobbles. Thus, further penetration is impossible when a few large cobbles or boulders collect in the bottom of the hole. If the boulders are relatively stable in the hole, a roller cone bit can be used to grind them into small fragments: cement may be used to stabilize the boulders prior to grinding.

Most new drill pipe used in reverse circulation rotary drilling is threaded and coupled pipe that can be as much as 8 inches in diameter and operated at depths of 2,000 ft or more.

Reverse circulation drilling is most successful in soft sedimentary rocks and unconsolidated sand and gravel where the static water level is 10 ft or more below ground level. In cases of high static water level, ramps are built above glade to support the drilling rig, or the weight of the drilling fluid is increased to obtain the necessary hydrostatic pressure. The reverse circulation drilling method may not be satisfactory when the static water level is too high and adequate water supplies are not available.

Advantages of the reverse circulation method include the following:

1. The porosity and permeability of the formation near the bore hole is relatively undisturbed compared to other methods.
2. Large diameter holes can be drilled quickly and economically.
3. No casing is required during the drilling operation.
4. Well screens can be set easily as part of the casing installation.
5. Most geologic formations can be drilled, with the exception of igneous and metamorphic rocks.
6. Little opportunity exists for washouts in the borehole because of the low velocity of the drilling fluid.

Disadvantages include the following:

1. Large water supply is generally needed.
2. Reverse rotary rigs and components are usually larger and thus more expensive.
3. Large mud pits are required.
4. Some drill sites are inaccessible because of the rig size.
5. For efficient operation more personnel are generally required than for other drilling methods.

4.4. AIR DRILLING SYSTEMS

Two different drilling methods use air as the primary drilling fluid—direct rotary air and down hole air hammer. In conventional reverse circulation methods, air is used as an assist but not as the primary drilling fluid. In the air rotary method, air alone lifts the cuttings from the borehole. A large compressor provides air that is piped to the swivel hose connected to the top of the kelly or drill pipe. The air, forced down the drill pipe, escapes through sumps at the bottom of the drill bit, thereby lifting the cuttings and cooling the bit. The cuttings are blown out the top of the hole and collect at the surface around the borehole. Injecting a small volume of water or surfactant and water (foam) into the air system controls dust and lowers the temperature of the air so that the swivel is cooled. Air drilling can be done only in semiconsolidated or consolidated materials. Therefore, to achieve the capability to operate in completely unconsolidated as well as consolidated formations, air rotary drilling machines are often equipped with a mud pump in addition to a high capacity air compressor. Conventional water based drilling fluids are then used when drilling through the overlying, caving formations above the bedrock (or more consolidated formations), whereas air is used once bedrock has been reached. Thus drillers are utilizing various options of drilling technology to adjust to the different physical characteristics of the formation. In many instances, caving may have to be installed through the overburden to avoid caving or excessive erosion of the borehole wall after changing to air circulation.

Cuttings are removed by grinding the material finely enough so that the uphole velocity of the air is sufficient to lift them to the surface. The lifting capacity of the air can be enhanced by adding a small amount of surfactant and water solution to the air. Larger cuttings can then be removed, thereby increasing the drilling rate. Foam also reduces loss of air to the formation. Suggestions for use of various drilling fluid additives are presented in Chapter 5.

![WELL DRILLING SELECTION GUIDE](image)

**Figure 4.5. Guide for the use of bit types in air-drilling systems. (Ingersoll-Rand)**

Roller-type rock bits, similar to those designed for drilling with water-based fluids, can be used when
drilling with air. Tricone rock bits up to about 12-in diameter are commonly used. Larger sizes are available. Button bits, made with sintered tungsten-carbide inserts set into the perimeters of steel rollers, are used successfully in many areas. Figure 4.5 lists the formations drilled effectively by carbide and steel-tooth bits in rotary air drilling.

Weld tests with various sizes of bits have shown that the penetration rate is often faster and the bit life longer when using air as compared with water-based drilling fluids. Better bottom-hole cleaning is partly responsible for this difference in performance. If too much water comes into the hole during drilling, however the penetration rate is no better than when drilling with water-based drilling fluids. Air also keeps the bit bearings cool and clean and causes some oxidation of the bearings: the oxidized material then becomes a lubricant. On the other hand, water-based drilling fluids are often abrasive and cause wear on the bearings.

A second direct rotary method using air is called the "down-hole" drilling system. A pneumatic drill operated at the end of the drill pipe rapidly stakes the rock while the drill pipe is slowly rotated. The percussion effect is similar to the blows delivered by a cable tool bit. The hammer is constructed from alloy steel with heavy tungsten-carbide inserts that provide the cutting or chipping surfaces. Tungsten-carbide is extremely resistant to abrasion, but drill bits do become dull with continued use. The inserts are sharpened by grinding when operating conditions indicate that the bit is not cutting properly. Alternatively, the bits can be provided with carbide buttons that can be periodically replaced when worn.

Rotation of the bit helps to assure even penetration and, therefore, straighter holes even in extremely abrasive or resistant rock types. The rates of penetration in several rock types are higher than those obtained by other drilling methods or other types of tools. 6-in and 6-1/2-in hammer bits are most commonly used, although sizes range up to 17-1/2-in. Cuttings are removed continuously by the air used to drive the hammer. Unlike the conventional cable tool bit that is constantly striking previously broken rock fragments, the bit (or buttons) on the air hammer always strike a clean surface. Thus, the air hammer is highly efficient.

Compressed air must be supplied to the hemmer at a pressure of 100 to 110 psi. Some tools require as much as 200 psi. To remove cuttings effectively, the upward velocity in the space outside the drill pipe should be about 3,000 ft/min or more. For drilling 4-in holes, the air supply must be at least 100 cfm (assuming a 2-7/8-in drill rod); for 6-in holes, at least 330 cfm is needed. Proper rotation speed is from 10 to 30 rpm; reduced speed is best in harder and more abrasive rock.

Advantages of using air drilling methods include the following:

1. Cuttings removal is extremely rapid.
2. Aquifer is not plugged with drilling fluids.
3. No maintenance costs for mud pumps (mud pumps are not used during air drilling).
4. Bit life is extended.
5. Drilling operations are not hampered by extremely cold weather.
6. Penetration rates are high, especially with down-hole hammers, in highly resistant rocks such as dolomite or basalt.
7. An estimate can be made during drilling of the yield from a particular formation.

Disadvantages include the following:

1. Restricted to semiconsolidated and well-consolidated materials.
2. Initial cost and maintenance costs of large air compressors are high.
4.5. IN-VERSE DRILLING

A recent innovation for the top-head drive, direct rotary machine involves the addition of an air assist by using a special 6-in inside diameter, side discharge swivel assembly and 5-7/8 in drill pipe with built-in air channels. This equipment permits compressed air to be injected through an injection stem into air channels mounted outside the drill pipe and then into the drilling fluid as it moves up inside the drill pipe (Figure 4.6). Thus, the drilling fluid and cuttings are assisted to the surface by an airlift inside the 6-in diameter conductor (drill) pipe. This method is known as the In-Verse system and converts a direct rotary, towhead drive machine into a reverse circulation rig. Use of the In-Verse system can increase the capacity of a direct rotary rig to drill large-diameter wells. Depending on the rig, boreholes from 20 to 30 in can be drilled routinely. If the pulling capabilities of the rig are sufficient, enough torque is available, and larger bits can be accommodated under the centralizer, boreholes of 30 to 60 in are possible in
unconsolidated formations. Boreholes smaller than 12 in are not recommended because the drill pipe has an outside diameter of approximately 9 in at the tool joint and significant erosion of the borehole wall may occur depending on the degree of formation consolidation.

It is recommended that at least a 300 cfm compressor operating at 125 psi be used for the In-Verse system. At this pressure, the maximum stem submergence is approximately 250 ft. If the borehole must extend past 250 ft 50 to 60 ft of drill pipe are pulled and another injector stem is installed in the drill string. Thus, if the drilling rig is equipped with only 250 ft of air channel pipe and the hole will be 500 ft deep, the drill pipe with the air channels must be mounted above the conventional drill pipe for any depth over 250 ft. This requirement increases drill pipe handling time somewhat.

The In-Verse equipped rig operates most satisfactorily with a centrifugal pump or a 3 x 4 or 5 x 6 piston pump. The latter pump will operate at approximately 300 psi. This size pump would be required to drill test holes or wells smaller than 12 inches in diameter using direct rotary drilling.

Advantages of the In-Verse system include the following:

1. Large-diameter boreholes can be drilled.
2. Penetration rates are high in unconsolidated sediments.
3. Less drilling fluid additives are required to lift the cuttings.
4. Development time is reduced.

Disadvantages include the following:

1. Extra costs for drip pipe, special swivel and air compressor (if the rig is not equipped with one).
2. Drill pipe handling time may increase for deep holes.

4.6 DUAL WALL REVERSE CIRCULATION ROTARY METHOD

In mining exploration, a drilling system called the dual wall method has been used for many years to obtain accurate geologic samples from known depths. The dual wall method uses flush jointed, double wall pipe in which the drilling fluid (air or liquid) moves by reverse circulation (Figure 4.7). Unlike conventional reverse circulation, however, the drilling fluid does not run down the outside of the drill pipe. Instead, the flow is contained between the two walls of the dual wall pipe and only contacts the walls of the borehole near the bit. Recently this method has been applied to water well exploration and construction in all types of geologic formations, although its principal use is still test drilling

Available drill pipe diameters for the dual-wall method are:

- 3-1/2 in OD x 1-3/4 in ID
- 4-1/2 in OD x 2-1/2 in ID
- 5-1/2 in OD x 3-1/4 in ID
- 6-5/8 in OD x 4-1/4 in ID
- 9-5/8 in OD x 6-1/4 in ID

The 4-1/2 in OD size is the most common. Male and female tool joints are used to connect the outer pipes; a connector sleeve with an "O" ring seals the joint between the inner pipes.
Dual-wall pipe can be driven into place in loosely consolidated materials by a steam, gasoline, or diesel operated pile hammer as the formation is being cut by a drive bit. Air or water is forced down the annulus to lift the cuttings to the surface through the inner pipe. If bedrock is reached, drilling may be continued by direct rotary methods using the dual-wall pipe as temporary casing. The pile driving method is generally not used in the water well industry because the hammering compacts unconsolidated formation materials. In addition, the method may not penetrate deeply enough for most water well applications.

More frequently, dual-wall pipe is set by standard reverse circulation methods using a top head-drive unit. The top-head drive should deliver about 4,500 to 5,000 ft-lb of torque to be effective. Down-the-hole air hammers and tricone bits can be used to cut the formation. As in the pile-driving method, air or water lifts the cuttings. Surface casing is not needed when the dual-wall system is used.

The outer pipe of the dual-wall system must be able to operate within the normal tensile, column, and collapse pressures associated with rotary drilling. The inner pipe is under little physical stress, but the abrasion caused by earth materials moving up the pipe from the bit causes wear. In practice this abrasion will generally cause the inner pipe to wear out more rapidly than the outer pipe. The inner pipe can be replaced if necessary.
If dual-wall casing is being set by a top-head drive, several different types of bits can be used, but the bit size is normally one nominal size larger than the drill pipe. Thus, the space between the outer pipe and the borehole wall is small and the pipe partially (or totally) supports the wall like a conventional stabilizer. The bit is counted into a permanent sub that has ports for passage of the drilling fluid. If a tricone bit is used, the drilling fluid passes upward through the inner part of the bit. A bit-wear sleeve is attached as close as possible to the cutting face and serves as a wear ring. The drilling fluid passes from the annular space between the two pipes, through a predrilled bit sub, and is discharged toward the cutting surface along the periphery of the bit sleeve; after entraining the cuttings, the fluid passes upward through the inner pipe.

![Diagram of dual-wall casing setup and bit installation](image)

**Figure 4.8.** The cross-over channel in the interchange sub mounted on top of the hammer permits the cuttings to enter the inner casing. (Drilling Services Company)

When a tricone bit is used, the formation sample passing upward through the inner casing originates from a small vertical section of the formation. In the use of a down-the-hole hammer, however, the bit extends 4 to 5 ft out from the bottom of the dual-wall pipe. Air is forced down inside the hammer, out the ports, and then passes up around the outside of the hammer shaft and into a special type of crossover channel (interchange) sub and then into the inner casing (Figure 4.8). Thus, the formation sample or water sample passing up the pipe can originate over a longer vertical section (3 to 4 ft) of the formation. It must be remembered, however, that this distance is still small when compared with intervals sampled by other types of rotary air drilling.

At the surface, drilling fluid enters the annular space between the inner and outer pipes by a special side inlet swivel. Drilling fluids can consist of dry air, air and water, air and water with surfactants, or water with clay or polymers. When air is used, velocities in the dual-wall system average 4,500 to 6,000 ft/min. After passing down the annular space and up inside the inner pipe, air passes with the formation sample
into a cyclone that can be equipped with an automatic splitter. The sample is collected in a sample bag. Under ordinary drilling conditions, 5 ft of sample bag will be filled for every 20 ft of hole drilled.

In the past, most boreholes drilled using the dual-wall method rarely exceeded 500 ft. Recently, however, depths of 800 to 1,400 ft have been reached by using booster compressors.

Screens and conventional casing can be installed when using the dual-wall drilling method. Screen and casing can be washed in over the dual pipes; small-diameter screens (1 to 2 in) can be installed through the bit; or the dual pipe can be pulled from the hole before a screen and casing are set.

Advantages of the dual-wall system include the following:

1. Continuous representative formation and water samples can be obtained.
2. Estimates of aquifer yield can be made easily at many depths in the connation.
3. Fast penetration rates are possible in coarse alluvial deposits or broken or fissured rock.
4. Problems of lost circulation are either eliminated or reduced drastically.
5. Washout zones are reduced or eliminated.

Disadvantages of the dual-wall system include the following:

1. Initial cost of drilling rig and equipment is high.
2. System is limited to rather slim holes (less than 9 to 10 in).
3. System is limited to depths of approximately 1,200 to 1,400 ft in alluvial deposits (works best to 600 ft) and generally up to 2,000 ft in hard rocks.
4. Well-trained drilling crews are needed.

4.7. DRILL-THROUGH CASING DRIVER

Drilling rig manufacturers have long sought to build drilling machines that could combine the hole stability of the cable tool rig and the speed of an air rotary rig. Some manufacturers are now providing casing drivers that can be fitted to top-head drive, direct air rotary rigs (Figure 4.9). The driver can be suspended in the most independent of the rotary drive unit because of its rather short length. Use of a casing driver permits the casing to be advanced during drilling, but both drilling and driving can be adjusted independently depending on the nature of the formation. Drivers are usually equipped so that they can be used to drive upward to remove casing or expose a screen. In the casing driver system, the drill pipe and casing are usually preassembled as a unit (must be the same length, usually 20 ft) and raised into position on the mast. The bottom of the casing is fitted with a forged or cast alloy steel drive shoe as in cable tool operations. A bit that fits inside the casing is attached to the bottom of the drill pipe. The top of the casing fits in the bottom of the casing driver by means of an anvil. The casing is driven by a piston that is activated by air pressure. Table 4.1 shows this relationship between air pressure, air consumption, and blows per minute for two sizes of drivers.
Three drilling procedures can be followed when using the casing driver (1) the drill bit and casing advance as a unit, (2) the casing is driven first (in unconsolidated materials only) and then the plug in the casing is drilled out, and (3) the drill bit advances beyond the casing a few feet, is withdrawn into the casing, and then the casing is driven.

As drilling commences using the first procedure, the cone-type bit protrudes out the bottom of the casing, but rarely more than 12 in. Cuttings are blown up the short open hole into the casing, and pass out the top through a horizontal tube during drilling, the casing is simultaneously driven into the ground; that is, the casing advances at the same rate as the drill bit. The dealer adjusts the pulldown and distance the bit is outside the casing according to the rate of advance and speed of cuttings removal. Occasionally the bit may be pulled up within the casing for a few moments to allow the air pressure to blow out the cuttings. Cuttings removal is facilitated by periodically adding small volumes of water if the borehole has not encountered water. This method is particularly suitable for drilling in stratified deposits that have large differences in particle size, for example, sand and silt to boulders.

In the second procedure, the casing is driven into the ground approximately 0.5 to 1.5 ft and the plug in the casing is then drilled out. The casing is usually driven only short distances so that each formation can be identified and sampled. During the casing-driving procedure, the drill bit is withdrawn inside the
casing and rotation is continued. Air is constantly circulated down the drill pipe to prevent clogging of the casing.

In the third procedure, the drill bit advances out the end of the casing a few feet. When the hole begins to become unstable, the bit is retracted into the casing and the casing is driven with the air pressure still applied to the borehole. This method is particularly successful in semiconsolidated sands, but also functions well in loose alluvium.

The drill-through casing driver arrangement achieves high drilling rates in most unconsolidated formations, even in bouldery till. In fact, welding two joints of casing together often requires more time than drilling and driving a 20-ft section of casing. When welding casing, some drillers weld straps across the welded joint for added strength. If rock underlies an unconsolidated formation, a down-the-hole hammer can be substituted for the cone bit once the casing is seated in the rock.

Table 4.1. Relationship Between Air Pressure, Air Consumption, and Blows per Minute for Two Sizes of Casing Drivers

<table>
<thead>
<tr>
<th></th>
<th>Banger Model</th>
<th>Slammer Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air pressure at:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 blows/min</td>
<td>40 psi</td>
<td>50-60 blows/min</td>
</tr>
<tr>
<td>120 blows/min</td>
<td>80 psi</td>
<td>90-100 blows/min</td>
</tr>
<tr>
<td>Air consumption</td>
<td>245 cfm</td>
<td>Air consumption</td>
</tr>
<tr>
<td>Driving Energy</td>
<td>2,100 ft/lb</td>
<td>Driving Energy</td>
</tr>
</tbody>
</table>

(Tiegre Tierra, Inc.)

If a screen is to be set, the casing can be pulled back by the top-head drive line, casing line, or, if some simple adjustments are made, by the casing driver (the driver can be adjusted to drive upward). It is wise to add a short piece of riser pipe to the top of the screen to prevent its loss if the casing is pulled back too far.

For some borehole diameters, it is possible to eliminate the casing driver but still drill and install casing at the same time. In loose overburden, an eccentric (off-centered) bit unit can be attached to a down-the-hole hammer. In this arrangement, the bit can cut a borehole slightly larger than the casing, allowing the casing to drop into place under its own weight. It may be necessary to drive the casing occasionally if it does not fall into place. This can be done in shallow holes by bringing the down-the-hole hammer out of the hole and driving on a driving cap placed on top of the casing. When consolidated rock is reached and the casing is seated, the rotation of the drill string is reversed for one revolution, causing the eccentric bit to center itself in the casing. It can then be withdrawn from the borehole and a conventional bit attached to the drill pipe. The new bit will cut a hole slightly smaller than the casing diameter.

The ability to drill and drive casing simultaneously is a major technological advance. It reduces costs and minimizes operational difficulties for the drilling contractor, especially during extremely cold weather. The drill-through casing method is particularly successful in bouldery tills or coarse, highly stratified alluvial deposits where rotary methods are ineffective or cable tool methods too time consuming.

Advantages of using the drill-through casing driver include the following:
1. Wells can be drilled in unconsolidated geologic materials that may be difficult to drill with cable tool or direct rotary methods.
2. Unlike other rotary methods, the borehole is fully stabilized during the entire drilling operation.
3. Penetration rates are rapid even under difficult drilling conditions.
4. Lost-circulation problems are eliminated.
5. Accurate formation and water samples can be obtained.
6. Casing drivers can be used in all weather conditions.
7. No water-based drilling fluid is required in unconsolidated materials.

Disadvantages include the following:

1. Additional cost of the casing driver.
2. Noise of operation (driving casing).

When air drilling techniques are used, the driller can easily see how much water is being blown out with the cuttings as the hole is deepened. From this observation, the driller can estimate when the borehole is deep enough to produce the desired yield. When static water levels are low, however, the air pressure in the hole may prevent water from entering the borehole.

The cost per foot of drilling with the air rotary system in consolidated formations is sensitive to the life and cost of the bits as well as to penetration rates. Experience in a given locality for specific types of consolidated rock must be depended upon for choosing the bit type that produces the best results economically.

**4.8. BORING WITH EARTH AUGERS**

Earth augers of various sizes and designs are used in certain areas for drilling water wells. Three principal types are used commonly: (1) large-diameter bucket auger, (2) solid-stem auger, and (3) hollow-stem auger.

**4.8.1. Bucket Auger**

The first method utilizes a large-diameter bucket auger to excavate earth materials. This method is referred to as rotary bucket drilling. The excavated material is collected in a cylindrical bucket that has auger-type cutting blades on the bottom. The bucket is attached to the lower end of a kelly bar that passes through and is rotated by a large ring gear that serves as a rotary table.

The kelly is square in cross section and consists of two or more lengths of square tubing, one length telescoped inside the other. This design permits boning to a depth several times the collapsed length of the kelly bar before having to add a length of drill rod between the kelly and bucket. In drilling with only the telescoping kelly serving as the drill stem, the bucket is lifted from the hole and dumped without disconnecting. If one or more drill rods are used for deeper boring, the drill rods must be removed each time the bucket is brought to the surface.

Wells more than 250 ft deep have been drilled by this method, although depths of 50 to 150 ft are more common. Water wells drilled with the bucket auger are from 18 to 48 inches in diameter, but few wells are larger than 36 in. Special hardened teeth or tungsten carbide inserts are fixed to the cutting blades on the bottom of the bucket when augering in dense formations.
Rotary bucket drilling of water wells has found primary application in areas of clay formations that stand without caving while the borehole is drilled and pipe is installed to serve as well casing. Drilling in sand below the water table is difficult, but not impossible if the hole is kept full of water or drilling fluid. A considerable supply of water may be needed if the sand formation is quite permeable. Thus, many drillers will use drilling fluid additives such as bentonite or polymers to control fluid loss.

Cobbles and boulders can cause much difficulty in the bucket auger procedure because they must be picked out of the bottom of the hole individually by using an orange-peel bucket, stone tongs, or ram's-horn tool. The hole diameter must be large enough to permit the use of these tools when necessary.

In operation, an auger bit will remove a cylinder of material 24 to 48 in deep in a contiguous mass. Therefore, samples obtained by the bucket auger method are representative of the formation being drilled, unless sloughing or caving of the borehole walls has occurred.

4.8.2. Solid-Stem Auger

A second boring method uses a solid-stem auger with either a single flight (one section) or continuous flighting (multiple sections). Augers having a single section of flighting are commonly called earth augers, construction augers, or large diameter augers. Earth augers with diameters as large as 54 in have been used in shallow holes, but 14- to 24-inch single-flight augers are more common. Borehole depths of 60 ft are not unusual in stable ground using the smaller diameter augers.

Drilling rigs equipped with large-diameter earth augers are similar in most respects to bucket auger rigs. They usually employ a kelly bar drive system. As with bucket augers, special hardened teeth or cutters are used when angering through hard ground, cobbles, or soft rock. This method is ineffective in loose ground or when drilling below the water table. It is sometimes used to bore a large-diameter hole to the water table; thereafter, casing is set and other drilling methods are used to complete the well. Shallow water wells are often constructed by augering to the top of a sand aquifer, lowering small-diameter pipe to that depth, and then advancing the pipe into the saturated formation by a bail-down or jetting operation.

Solid-stem augers with continuous flighting are used to advance holes in stable formations. Solid-stem augers are not truly solid, because the continuous flight design is welded onto small-diameter pipe; but the hexagonal pin placed at both ends of the flight (section) makes this type of auger nonhollow. Drill rigs turn the auger sections using a rotary drive head mounted on a hydraulic-feed mechanism that pushes the auger section down or pulls it back. Single auger lengths are generally 5 ft; diameters range from 4 to 24 in, with diameters of 6 to 14 in used in well drilling. Although depths of 400 ft have been recorded with the 6-in auger, auger depths of 40 to 120 ft are more usual for the common diameters.

For drilling, a special auger bit or cutter head is attached to the leading auger flight section and cuts a hole for the flights to follow. The cutter head is usually 2 in larger in diameter than the flights, providing about 1 in clearance. The cuttings are brought to the top of the hole by the flights which act as a screw conveyor. As the auger drills into the earth, more auger sections are added until the desired depth is reached or penetration is halted by obstructions, hard ground, or caving conditions.

4.8.3. Hollow-Stem Auger
The third augering method is the hollow-stem continuous-flight augering method. Although geotechnical and exploration drillers have been using the hollow-stem auger since the early 1950's its use by the water well drilling industry has been quite limited until recently. The flights for the hollow-stem auger are welded onto larger diameter pipe with a cutter head mounted at-the bottom (Figure 4.10). Unlike the solid-stem method, drill rods (drill stems) can pass through the center of the auger sections. A plug is inserted into the hollow center of the cutter head to prevent soil from coming up inside the auger. This center plug has an attached bit that helps advance the auger. The drill rod and plug connect through the auger flights to the top-head drive unit by small-diameter drill rods to insure that the drill rods and plug rotate with the flights.

Hollow-stem augers with outside diameters ranging from 6-1/4 to 22 in (2-1/2 to 13 in ID) have been used to drill water wells, although the common outside diameters are 6-1/4 to 13 in ID. Auger lengths are usually 5 ft. but on larger hollow-stem rigs, especially those equipped with carousel racks, the auger flights are 10 ft long and are stored in 20-ft sections. Holes as deep as 300 ft have been drilled with 6-1/4-in diameter hollow-stem augers; more corrosion depths in stable formations are 120 ft with 6-1/4-in diameter hollow-stem augers and 40 ft with 12-in diameter hollow-stem augers. Hollow-stem augers are more effective than solid-stem augers because they can be used as temporary casing to prevent caving and sloughing of the borehole wall. The hollow-stem method is a fast and efficient means of drilling and completing small diameter wells to moderate depths. Screens can be installed and filter packed without using casing or drilling fluids. Use of the hollow-stem auger method is also particularly advantageous in obtaining accurate samples. A major disadvantage of this method is the relatively high cost of hollow-stem flight augers.
Figure 4.10. The lowest flight in a hollow-stem auger drill string is equipped with a cutter head and a pilot bit. (Mobile Drilling Company, Inc.)
4.9. DRILLING PROCEDURES WHEN BOULDERS ARE ENCOUNTERED

In many formations, boulders or large cobbles can slow or even stop drilling progress regardless of the drilling method being used. If the casing or borehole is being deflected, the driller must do something about the boulders before drilling can be continued. Boulders occur commonly in glacial tills, extremely coarse outwash deposits, former beach zones now buried, conglomerate deposits that formed near the base of steep slopes, alluvial fans, and alluvial deposits in mountainous regions. Drilling costs can rise significantly when boulders are encountered in the hole.

In general, do not drill below a protruding boulder because it may fall partly into the hole causing the bit to become lodged. Whether boulders are removed or destroyed will depend on the drilling method being used. Alternative procedures include the following:

4.9.1. Cable Tool:

1. Change the bit.
2. Increase drill-string weight to break the rocks.
3. Bail out material below the boulder so that it drops into the hole. Fluid levels may have to be increased to keep the borehole open.

4.9.2. Direct Rotary:

1. Increase the weight on the bit to grind through or crush the rock or force it to the side of the borehole.
2. Install a new or different bit.
3. Fish out the boulder if it is completely within the borehole.
4. Switch to air and use an air hammer.
5. Cement the boulder if it is sufficiently far above the aquifer, then continue drilling.

4.9.3. Reverse Rotary:

1. Install a new bit to either push the boulder into the borehole or grind up the rock, cement can be used to stabilize the rock (if boulders are not near the aquifer).
2. Increase the weight on the bit.
3. Fish out the boulder.

4.9.4. Air Rotary with Casing Driver:

1. Keep the bit close to the bottom of the casing so boulders cannot become lodged between the bit and casing.
2. Drill and drive only short distances.
3. Increase the weight on the bit.
4. Pull back slightly allow the boulder to fall into the borehole or be pushed into die borehole wall.
5. Change the bit, preferably to a down-the-hole hammer.
6. If boulders are sufficiently far above the aquifer, cement them into position so they can be drilled.

4.9.5. Several general points can be made concerning drilling through boulders:
1. The driller should proceed cautiously to prevent damaging the drive shoe or deflecting the casing.
2. It may be best to case through boulders.
3. Drill at least 5 to 10 ft into the rock to make sure that bedrock has been reached.
4. If the casing has been dented by a boulder during driving, the casing diameter should be restored by using a casing swedge (the swedge is also useful in lining up broken casing so it can be lined with a sleeve).

4.10. FISHING TOOLS

In most drilling methods, tools can be broken off or dropped into the borehole. The object or tool that is lost in the hole is called the "fish," which the driller retrieves by "fishing." Fishing jars are used in the cable tool method to retrieve tools from the hole. They are placed between the fishing stem (usually 10 ft long) and a fishing tool such as a ham socket or center spear. In this position, the stem increases the impact of the jars on the fishing tool during the upstroke. The greater stroke of the fishing jars prevents accidental downstroke hitting during retrieval of the lost tool. Hitting both up and down will usually free the "fish" to be removed from the hole.

In the rotary drilling method, the shear stresses placed on the drill string are often excessive, unlike the cable tool method where only the force of gravity is utilized for drilling. These shearing stresses are magnified because the weight of the entire drill column is augmented by the hydraulic driven pull-down weight that may be applied by the driller. These pull-down weights may reach 30,000 lb or more. Because the torque applied to the drill string can occasionally exceed the breaking strength of the equipment, special fishing tools have been developed to extract pieces of the sheared drill string from the hole.

Six fishing tools are used most commonly in rotary drilling operations: tapered tap, die collar, releasing spear, junk mill, circulating overshot, and magnet. Many drillers construct fishing tools that may be particularly suitable for their own equipment. After determining the depth at which the string or tool has been lost, the driller attempts to enter or overshoot the top of the lost drill rod and then rotate the fishing tool until it is firmly attached. Releasing spears can be used in place of a taper tap. They offer the advantage of quick release from the fish and provide easy re-engagement if necessary. If greater force is required to pull the fish, another type of tool called a releasing and circulating overshot is used. It consists of three main components—a top sub, a bowl that houses the engaging and packing-off element, and a "guide to center the tool over the fish. A junk mill is used to grind up smaller objects lost in the borehole. Powerful magnets are useful in moving relatively small tools or other parts from the hole. To be successful, circulation must be established or maintained during most fishing operations.

One particularly common fishing operation in large-diameter holes involves retrieval of roller cones that have become detached from the bit. Failure of the bearings on which the cones rotate is the principal cause of cones falling to the bottom of the borehole. Bearing failure is usually attributable to excess weight on the bit, high operating temperatures, or excessive use. The most common techniques for retrieval of lost cones include the use of a junk basket, a strong magnet, or a button or diamond bit to grind up the cone. Lost cones can sometimes cause abandonment of the well. To avoid this problem, the driller should immediately replace any bit on which a cone has become damaged or locked in place.

4.11. GRATING AND SEALING WELL CASING
In engineering practice, grouting is the act of injecting certain substances into the void space of earth materials to reduce or eliminate their permeability, consolidate them, or increase their strength (Bower, 1981). Thus, grouting is widely used in constructing tunnels, dams, bridges, and foundations for buildings. Low-viscosity grouting materials are used in soils having low hydraulic conductivity, whereas high viscosity grouts are used in coarse-grained, highly permeable soils. Although several basic types of grouting materials exist, multiphase (suspension) systems are common in the water well industry.

Grouting (cementing) well casing involves filling the annular space between the casing and the drilled hole with a suitable slurry. The term "grouting" is used by drillers to describe the process of mixing and placing grout. The length of the borehole section to be grouted will vary according to well codes, aquifer structure, and water quality.

Wells constructed in rock that is overlain by relatively thin, loosely consolidated sediment will usually be grouted from the surface to the rock. In some formations where poor-quality aquifers are interspersed with high-quality water zones, the poor-quality aquifers are cemented off. Grouting is also standard practice in monitoring well construction.

The grouting methods described below focus primarily on the use of cement and water (neat cement), although the slurry may contain sand and bentonite. A clay slurry made with a high-grade bentonite can serve for grouting, provided it is used at a depth where drying and shrinking of the grout will not occur, and where water movement will not wash away the clay particles.

Various types of cement are manufactured to accommodate different chemical and physical conditions found in the subsurface environment. Five types are given in ASTM specifications and are used generally at the ground surface. The high pressures and temperatures encountered in deep wells, especially oil wells, has led to the development of eight classes of cement under API specifications.

The compressive strengths of portland (types A and B) and high early cements (type C) are shown in Table 4.2 for setting times of 24 and 72 hours at various temperatures. Various compositions of cement have different compressive and tensile strengths after curing; compressive strengths are usually about 10 times greater than tensile strengths. For most drilling operations, the cement should reach a compressive strength of 500 psi before drilling is resumed. The temperature in the borehole, chemistry of the formation water, dilution of the cement, and downhole pressure affect the rate at which the cement cures. Generally, the 500 psi compressive strength is reached between 12 and 24 hours after placement.

The chemical reaction that causes gout to set and harden begins as soon as cement and water are mixed. The equipment used to mix and place the grout must be adequate to complete the installation while the grout is still fluid.

The size of the annular space required for grouting depends on the method of grouting. Thus, planning the size of the borehole is important. The annular space to be grouted should have a diameter that is 2.0 to 8.0 in larger than the casing. The ideal result is a uniform sheath of cement around the casing for the entire vertical distance to be grouted. Tight places and "dead spots" result where casing not properly centered touches the wall of the hole, causing channeling of the slurry.
State or federal laws may dictate the minimum length of grout required for various casing diameters for certain types of wells. The drilling contractor should become familiar with specific regulations for the type of wells drilled.

### 4.11.1. Proportioning Cement Grout

Laboratory tests indicate that 5.2 gal of water are needed to hydrolyze one 94-lb sack of portland cement. This mixture produces a slurry weight of 15.6 lb/gal. An advantage of using the proper water-cement ratio is more effective bridging of cement particles in the pores of permeable formations, which prevents excessive penetration of the grout into these formations. Although thinner mixtures with more than 6 gal per sack are used for grouting foundation materials, this ratio is less suitable for well work. Shrinkage increases with greater water content, because water is squeezed out of the thinner mixtures by pressure against fine sand or other permeable formation materials. Cement will settle out of the slurry if the ratio is greater than 10 gal per sack of cement. Water used for grout should be free of oil and other organic material.

Bentonite clay can be added to the cement to hold cement particles in suspension, reduce shrinkage, and improve fluidity of the mixture. Approximately 3 to 5 lb of bentonite should be mixed with 6.5 gal of water per sack of cement. If the amount of bentonite exceeds 6 percent, excessive shrinkage of the cement will occur. It is best to mix the bentonite and water few, then add cement to the clay-water suspension.

### 4.11.2. Mixing the Grout

It is important that grout be mixed thoroughly and be free of lumps. Some drillers use small portable grouting morphines that combine both the mixing and pumping operations. Many of these machines are equipped with a positive displacement pump because this type of pump can work efficiently against much greater head pressures with little loss in emplacement volume. Most drillers avoid using the mud pump on their rotary rigs because of the abrasive qualities of the cement and the difficulty in removing all traces of the cement from the pump after completing the cementing operation.

<table>
<thead>
<tr>
<th>Temperature °F °C</th>
<th>Borehole Pressure psi kPa</th>
<th>Typical Compressive Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24 Hours*</td>
<td>72 Hours*</td>
</tr>
<tr>
<td></td>
<td>Portland psi kPa</td>
<td>High Early psi kPa</td>
</tr>
<tr>
<td>60 15.6</td>
<td>0 0</td>
<td>615 4,240</td>
</tr>
<tr>
<td>80 26.7</td>
<td>0 0</td>
<td>1,470 10,140</td>
</tr>
<tr>
<td>95 35.0</td>
<td>800 5,520</td>
<td>2,085 14,380</td>
</tr>
<tr>
<td>110 43.3</td>
<td>1,600 11,030</td>
<td>2,925 20,170</td>
</tr>
</tbody>
</table>

*Strengths based on the following criteria:

- Water: 5.19 gal/sack
- Slurry weight: 15.6 lb/gal
- Slurry volume: 1.18 ft³/sack

Table 4.2. Compressive Strengths of Portland and High Early Cement

(State or federal laws may dictate the minimum length of grout required for various casing diameters for certain types of wells. The drilling contractor should become familiar with specific regulations for the type of wells drilled.)
The volume of grout required cannot always be determined accurately. Regularities in the size of the borehole and losses into fractured rock occur in many wells. Therefore, the driller must be prepared to augment initial estimates on short notice.

When water is mixed with cement and hydration occurs, heat is released. The amount of heat released is a function of the volume of cement—the more cement, the more heat. If the formation temperature is high, the hydration process is accelerated and heat is released more quickly. If cement fills a 2-in annulus, the heat produced during hydration creates a maximum temperature rise of 35° to 45°F.

4.11.3. Slurry Placement Methods

Successful placement of the cement will depend on the temperature and pressure in the borehole, how well the casing is centered in the hole, and the emplacement method. Temperature has a significant effect on how fast the cement slurry hydrates and thus how fast the cement develops strength. Pressures caused by the weight of the drilling fluid can reduce the rate at which the cement can be pumped. At high pressures (only a problem in deep water wells), the hardening time for the cement can be substantially reduced. The use of centralizers is important to assure a uniform thickness of cement around the casing. Centralizers should be placed every 40 ft on the casing. Several placement methods are described below. Each method is satisfactory but care should be taken to assure that channeling does not occur, thus avoiding gaps in the cement.

To assure that grout will provide a satisfactory seal, it is necessary to place it in one continuous operation, before setting begins. Regardless of the grouting method used, the grout should be introduced first at the bottom of the space to be grouted. This procedure minces both contamination or dilution of the slurry and bridging of the mixture. If the cement is pumped under turbulent flow conditions, drilling fluid removal is enhanced and voids are filled more completely.

Moyno, diaphragm, and piston pumps are most often used to pump cement grout. The Moyno pump is a positive displacement pump with an effective output pressure of 225 to 250 psi; it cannot be permitted to pump sand, however. Diaphragm pumps, although having lower output pressures of 100 to 110 psi, can handle particles up to 1/4 to 3/8 inches in diameter. They are not as efficient as the Moyno pump because of higher friction losses. Both types are used for batch mixing.

For larger grouting jobs, either piston pumps or, less frequency, centrifugal pumps are favored. Piston pumps of various sizes (2 x 3, 3 x 4, or 5 x 6) can build pressures to 120 psi, and have been used successfully to place grout to 3,000 ft or more with a 2-in tremie pipe.

In cases where an open borehole has been drilled below the depth to which the casing is to be grouted, the lower part of the hole must be backfilled, or a bridge (cementing basket or formation packer shoe) must be set in the hole, to retain the slurry at the desired depth.

When the borehole cannot be backfilled, external packers combined with a float shoe or cement baskets are used to support the cement column. Cement baskets are installed on the outside of the casing by clamps. External packers must be installed in the casing string as the casing is run into the borehole; the packers are expanded before cementing begins.

Cement should be allowed to harden for 24 hours before drilling resumes, although some types of cement may require longer curing times.

4.11.4. Tremie Pipe Outside Casing
Grout can be placed through a string of small diameter pipe (tremie or grout pipe) placed outside the casing. The casing is lowered into the hole with centering guides attached. Care must be taken to align the centering guides along the entire length of casing to be grouted so that the tremie pipe can pass by them. The lower end of the casing should be closed with a drillable plug or driven into clay so the grout cannot enter. To overcome the buoyant effect of the slurry, the casing may be filled with water or be held down by the weight of the drill rig.

Grout can be placed by gravity through a tremie pipe, but pumping is preferred because the required volume of grout can be introduced rapidly and with little chance of leaving voids in the grout. Pump pressure must equal the hydrostatic pressure of the Bout the fluid friction in the grout pipe and annular space.

For shallow holes where the grout is placed by a positive displacement pump, the cementing operation may be completed in a single step; that is, the position of the tremie pipe is not changed as the annulus is filled. If a centrifugal pump is used or if the hole is deep, the tremie must be raised periodically so the hydraulic head created by the cement does not exceed the working pressure of the pump. Usually the tremie is withdrawn one or more joints at a time, but the bottom

![Diagram of grouting process](image)

*Figure 4.11. Grouting can be accomplished by means of a tremie pipe suspended in the annulus outside the casing. During grouting, the bottom of the tremie should always be submerged a few feet beneath the grout level. As the grout level rises, the tremie should be withdrawn at approximately the same rate.*

of the tremie should always remain beneath the surface of the cement. The rate of tremie withdrawal will depend on the pumping rate and the volume of the annulus. The depth to the top of the grout can be
detected by using a weighted line or a weight indicator. The volume (and therefore the height) of the grout can also be estimated by knowing the volume of material in the hopper before grouting begins.

The grout pipe must be large enough so that all the grout can be placed before hardening begins. A 3/4- or 1-in grout pipe may be used, although 2 in pipe is used for deeper holes. The borehole should be 4 to 8 in larger than the casing to accommodate the grout pipe. Initially, the pipe should extend to the bottom of the annular space and should remain submerged in the slurry while the grout is being placed (Figure 4.11). Should the tremie become plugged, the output pressure can be increased, the tremie can be raised to reduce the pressure at the bottom of the line, or it can be vibrated or struck to dislodge the stuck material. If operations are interrupted for any reason, the pipe should be raised above the grout level and not be lowered into the slurry again until all air and water in the pipe have been displaced by grout.

**4.11.5. Tremie Pipe Inside Casing (Inner String Method)**
When the use of a grout pipe outside the casing is impractical, grouting may be done by using a grout pipe installed temporarily within the casing (Figure 4.12). In the oil-well industry, this is referred to as the inner-string method of cementing. A cementing plug (float shoe) is attached to the bottom of the casing, which permits the grout to pass into the annular space but prevents it from leaking back into the casing while grouting or after removing the grout pipe.

In the grouting process, the casing is filled with water and suspended just above the bottom of the borehole. Grout is pumped through the grout pipe and—float shoe and forced upward around the casing. When cement appears at the surface, displacing all other fluid in the annular space, the grout pipe is disconnected from the float shoe. Cement is washed out of the pipe by pumping water through it before removing it from the well. Because calcium residues may have a deleterious effect on the viscosity-building characteristics of some drilling fluid additives, the casing should be completely flushed with clean water after completing the cementing operation.

![Diagram of grouting process](image)

**Figure 4.13. Grout can be placed in the casing and then forced out the bottom and up the annulus. This is called the casing method of placing grout. Plugs are used to separate the grout from the drilling fluid and the water used to drive the grout into place. The plugs and float shoe are drilled out after the grout hardens. The casing method of grouting was originally used in the oil-well industry.**

**4.11.6. Casing Method of Grouting**

The casing method of grouting, in which the slurry is forced down the casing and into the annular space, has been adopted from the oil-well industry. In one method, two spacer plugs are used. One plug, introduced first, separates the cement slurry above from the drilling fluid in the casing; the other separates the slurry from water pumped in above it to wash the slurry from the casing (Figure 4.13).

After punning water or drilling fluid through the casing to circulate fluid in the annular space and clear any obstructions from the hole, the first plug is inserted and the casing capped. A measured volume of grout is then pumped in, the casing is opened, a second plug is inserted, and the casing recapped. A measured volume of water is then added and pushed to the bottom of the casing, forcing most of the
cement slurry from the casing and into the annular space. The water in the casing is held under pressure to prevent backflow of the slurry until it has set and hardened. When the cement has hardened sufficiently, the second plug and any cement remaining in the casing are drilled out, drilling is continued below the grouted section, through the first plug and into the formation.

A modification of the double-plug procedure is favored by many drillers. After pumping a predetermined quantity of grout into the casing, a plug is installed on top of the grout and enough water is added to force most of the grout from the casing. The usual practice is to leave 10 to 15 ft of grout in the casing. If only a single plug is used, that part of the slurry diluted by the drilling fluid must be expelled to waste at the surface so that a sound, uncontaminated grout seal is achieved at the upper end of the casing. The use of a plug insures slurry and water separation, resulting in a proper grout seal at the lower end of the casing. To eliminate over or under displacement of the cement, a landing collar is set 10 to 20 ft above the bottom of the casing to stop the drivable plug at the appropriate depth.

Spacer plugs should be made of materials that can be drilled easily (wood and cement are often used). When a plug settles on sand or clay, the cushioning effect of the soft formation permits the plug to sink into the formation before it is drilled out.

4.11.7. Grouting Failures

Several factors may contribute to grouting failures. Some common problems are premature setting, partial setting, insufficient grout column length, voids or gaps in the grout, excessive shrinkage, and casing collapse. Premature setting of the cement can be a serious problem and is usually caused by incorrect assumptions concerning borehole temperature, or by hot mixing water, improper water-to-cement ratios, contaminants in the mixing water, mechanical failures, and interruptions of the pumping operation. Voids within the grouted annulus, another major grouting problem, are usually caused by contact of the casing with the borehole wall or by the presence of washouts.

4.11.8. Installation of Bentonite Grout

Bentonite (essentially montmorillonite) is widely used as a grouting material, especially for monitoring wells and water wells where surface contamination may occur, because of its low cost and ease of placement. Commercial bentonite used for grouting is available in either pelletized or granular form. When either of these forms are mixed with water, they begin to hydrate within seconds. Thus, it is impossible to place the granular form by dropping the particles into the annulus. Even pellets dumped down the annulus will begin to stick together and to the walls of the annulus within a few feet of the surface, and therefore may bridge high above the intended depth. It is possible to freeze the pellets first and then carry them to the drilling site in a cooler containing dry ice. In this condition, the pellets will settle a greater distance before sticking. The pellets can also be cooled with liquid nitrogen; in this case, an icy outer layer forms which further protects the pellets so that they may fall 40 ft or more before hydration begins. In general the pellets should always be tamped into place to eliminate any bridging that may have occurred. A much better practice is to pump a prepared bentonite slurry by means of a tremie pipe, using a Moyno pump (40 to 60 gpm) or diaphragm pump (60 to 100 gpm). If the mixture of bentonite (usually granules) and water is used, only 1 lb of bentonite can be mixed per gal of water because the resulting viscosity will be at the limit of pumping capacity. After being placed, grout with this concentration of bentonite may eventually shrink 25 percent, even though the ground around the grout usually remains somewhat moist. This is a highly unsatisfactory shrinkage rate. Virtually no shrinkage will occur in grout mixed at concentrations of 1.5 lb bentonite per gal of water. This concentration can be pumped only if the water has been pretreated with 1 qt of polymer per 100 gal. The
polymer prevents the clays from hydrating immediately, and once the particles are evenly distributed in the water the viscosity remains low enough so the slurry can be pumped for about 20 minutes. The granular Bentonite should be mixed gently into the water with a paddle, not a mixer or pump; these latter devices will break up the particles and cause the viscosity of the slurry to increase prematurely.

Bentonite grouts should be mixed in batches so they can be pumped before the slurry becomes too viscous. Ideally, the diameter of the suction hose should be as large as possible. In most cases, the slurry reservoir is above the pump intake so that hydrostatic pressure created by the reservoir makes the pump operate more efficiency. The pump and all piping should be flushed with clean water after each batch of grout is pumped into place. The volumes of bentonite, polymer, and water for various annulus sizes, per 100 ft of depth, are given in Table 4.3.

<table>
<thead>
<tr>
<th></th>
<th>Bentonite</th>
<th>Water</th>
<th>Polymer*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lbs</td>
<td>gal</td>
<td>t</td>
</tr>
<tr>
<td>2-in (51-mm) pipe in</td>
<td>75</td>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>4-in (102-mm) hole</td>
<td>34</td>
<td>189</td>
<td>0.5</td>
</tr>
<tr>
<td>4-in (102-mm) pipe in</td>
<td>112</td>
<td>75</td>
<td>0.75</td>
</tr>
<tr>
<td>6-in (152-mm) hole</td>
<td>51</td>
<td>284</td>
<td>0.7</td>
</tr>
<tr>
<td>5-in (127-mm) pipe in</td>
<td>225</td>
<td>150</td>
<td>1.5</td>
</tr>
<tr>
<td>8-in (203-mm) hole</td>
<td>102</td>
<td>568</td>
<td>1.4</td>
</tr>
</tbody>
</table>

*Bentonite grout has several advantages over cement grout. It has a faster setting time, no heat of hydration, a lower hydrostatic pressure (specific gravity is 9.2 for the grout given in Table 4.3), and the cost is one-third that of cement. Also, Bentonite will adhere to both walls of the annulus, whereas cement will adhere finely only to the soil.

There are several limitations on the use of Bentonite grout. Bentonite grouts cannot be used when the borehole is underreamed, because the "set" taken by the grout is not sufficient to withstand the vertical hydrostatic pressures. Thus, the grout may eventually flow into the underreamed section.

Another limitation is that Bentonite grout should not extend so close to the ground surface that it can dry out and shrink because of low soil moisture. Cement is always used at or near the top of the borehole. The presence of salt water will cause Bentonite grout to flocculate and thereby lose viscosity. Organic acids can also destroy the impervious character of the grout seat.

4.12. PLUMBNESS AND ALIGNMENT

A well should be both straight and plumb, although in practice any borehole of substantial depth may not be perfectly straight perfectly plumb. A straight well is one in which each casing section is joined to adjacent sections in a manner that maintains perfect alignment. A borehole that is plumb is one whose center does not deviate from an imaginary vertical line running from the ground surface to the center of
the Earth. A well bore may be straight, but not plumb; if the borehole is plumb, however, it will be straight. Some tolerance or deviation in straightness (alignment) and
plumbness is normally allowed in practice. By custom, a deviation from plumbness of two-thirds the
well's inside diameter per 100 ft is allowed and thought to be reasonable, considering the inherent
difficulties of drilling in earth materials. The U.S. Environmental Protection Agency (1975) has
suggested that wells should be constructed so that the borehole deviation from plumbness is 1 degree or
less per 50 ft when using drift indicators.

<table>
<thead>
<tr>
<th>Table 4.4: Relative Performance of Different Drilling Methods in Various Types of Geologic Formations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Formation</td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>Dune sand</td>
</tr>
<tr>
<td>Loose sand and gravel</td>
</tr>
<tr>
<td>Quicksand</td>
</tr>
<tr>
<td>Loose boulders in alluvial fans or glacial drift</td>
</tr>
<tr>
<td>Clay and silt</td>
</tr>
<tr>
<td>Firm silt</td>
</tr>
<tr>
<td>Sticky shale</td>
</tr>
<tr>
<td>Brittle shale</td>
</tr>
<tr>
<td>Sandstone—poorly cemented</td>
</tr>
<tr>
<td>Sandstone—well cemented</td>
</tr>
<tr>
<td>Chert nodules</td>
</tr>
<tr>
<td>Limestone</td>
</tr>
<tr>
<td>Limestone with chert nodules</td>
</tr>
<tr>
<td>Limestone with small cracks of fractures</td>
</tr>
<tr>
<td>Limestone, cavernous</td>
</tr>
<tr>
<td>Dolomite</td>
</tr>
<tr>
<td>Basalts, thin layers in sedimentary rocks</td>
</tr>
<tr>
<td>Basalts—thick layers</td>
</tr>
<tr>
<td>Basalts—highly fractured (lost circulation zones)</td>
</tr>
<tr>
<td>Metamorphic rocks</td>
</tr>
</tbody>
</table>

*Assuming sufficient hydrostatic pressure is available to contain active sand (under high confining pressures)

Rate of Penetration:
1. Impossible
2. Difficult
3. Slow
4. Medium
5. Rapid
6. Very rapid
Of the two factors, straightness of the well bore is the most important.

Some conditions that cause wells to become misaligned and out of plumb are (1) character of the subsurface material (faults, boulders in the borehole, inclined strata), (2) too much or too little weight on the drill bit, (3) trueness of the casing and drill pipe, and (4) the pull-down force applied to the drill pipe in rotary drilling. While the force of gravity tends to make the drill bit cut a vertical hole, the varying hardness of different materials being penetrated deflects the bit from a truly vertical course. In glacial drift, the edge of a boulder can deflect a cable tool or rotary bit. In cable tool drilling, a boulder may deflect the well casing, causing the hole to drift increasingly as the well is deepened.

When drilling by the rotary method, too much force applied at the top of the drill stem will bend the slender column of drill pipe. This tends to cause the bit to cut off center. Heavy drill collars in the lower part of the drill stem help to put weight just above the bit, which overcomes the tendency to drift off a true vertical course. They are also more rigid than ordinary drill pipe, and thus help keep the lower part of the drill string straight. Large stabilizers are also used by many drillers to keep holes straight.

In recent years, special deviation instruments have been developed to measure the misalignment that occurs during drilling. A deviation survey is conducted along with the standard suite of logs after the maximum hole depth has been reached.

4.13. CONCLUSIONS

Selection of the best drilling method for a particular job requires an understanding of the geologic conditions and the physical limitations of the drilling rig. In addition, the value of experience cannot be overestimated, for many drilling difficulties occur because either the driller is unprepared to handle the wide range of subsurface conditions or has pushed the rig beyond safe operating limits. Good record keeping, patience, and a willingness to learn are some important characteristics of good drillers; the age of the machine or the particular drilling method used are of secondary importance in drilling successful wells. Table 4.4 gives the drilling performance of different drilling methods in various geologic formations. The relative performance differences between drilling methods, however, will also depend on the experience of the driller, the presence of geologic anomalies at the site, and the pressure conditions affecting the groundwater.

CHAPTER 5.

DRILLING FLUIDS

The technology of drilling fluids has advanced as rapidly and extensively as the rotary drilling machine. In the late 19th century, water alone was the principal fluid used in rotary drilling, although some entrainment of natural clay particles into the fluid must have occurred much of the time. The general term "mud" originated when certain kinds of clays were added to water to form drilling fluid. Recent advances, however, have made the term "mud" somewhat obsolete. Modern mud systems are now referred to as drilling fluids because of the large number of additives that can be used to impart special properties to drilling fluids. Much of the progress in drilling fluid development has occurred in the oil industry and has been applied thereafter in the water well industry. Today, the drilling fluid system can represent a major cost for deeper rotary-drilled holes; therefore, the economic success of the drilling
operation may be determined by the contractor’s ability to control the physical characteristics of the drilling fluid.

5.1. TYPES OF DRILLING FLUIDS

Drilling fluids used in the water well industry include water-based and air-based systems (Table 5.1). Water-based drilling fluids consist of (1) a liquid phase, (2) a suspended-particle (colloidal) phase, and (3) cuttings entrained during drilling. The colloidal phase may range from less than 1 percent to as much as 50 percent by volume. Air-based drilling fluids may consist of only a dry air phase, but more often they contain some water to which a surfactant (soap) is added to produce a foam. Occasionally a small amount of clay or polymer may be added to stiffen the foam. Thus, the primary drilling fluids, water and dry air, may be used alone, but a great variety of additives are available to modify their physical and chemical properties so they will perform more satisfactorily.

---

1 Suspended particles that are approximately 0.0005 to 0.5 microns in size, do not settle out of the liquid rapidly, and are not readily filtered. (There are 25,400 microns per inch.)
In this chapter, three major, but vastly different, types of drilling fluid additives are discussed and contrasted—clays, polymers, and surfactants. Clays and polymers are commonly added to waterbased systems and surfactants and occasionally clays or polymers are added to dry air systems.

Water with clay additives produces a high-solids drilling fluid, whereas a combination of polymeric additives and water produces a low-solids drilling fluid. Many other special additives, such as flocculants, thinning agents (dispersants), weighting materials, corrosion inhibitors, filtrate reducers, lubricants, preservatives, bactericides, and lost-circulation materials, are used to further adjust the properties of drilling fluids.

The exact driving fluid system selected will depend principally on the rock formation or stratigraphy expected and the equipment available. Drilling in hard rock for example, requires procedures different from drilling in sedimentary rock or unconsolidated overburden. Waterbased drilling fluid systems with clay or polymeric additives are typically used in unconsolidated formations; air is used in well-consolidated or semiconsolidated rocks and sediment; and clean water is used with reverse rotary drilling equipment for large diameter wells in unconsolidated, semiconsolidated, and nonsensitive (nonswelling) sediments.

5.2. FUNCTIONS OF A DRILLING FLUID

Drilling fluids can perform many functions, depending on the physical and chemical conditions found in the borehole. The primary functions are:

1. Remove cuttings. The primary purpose of the fluid system is to remove cuttings from the borehole during drilling. The rate at which cuttings can be removed depends on the viscosity, density, and uphole velocity of the drilling fluid, and the size, shape, and density of the cuttings. Ideally, the fluid should entrain the cuttings at the bit, carry them to the surface, and allow them to drop into a settling pit or tank before the fluid is recirculated. Inefficient removal of cuttings can reduce the penetration rate of the drill bit, adversely affect the physical properties of the drilling fluid, and increase the energy required to recirculate the drilling fluid.

2. Stabilize the borehole. To maintain an open borehole, the drilling fluid stabilizes the borehole walls and prevents expansion of swelling clays. When using water-based systems, the drilling fluid must provide a pressure greater than that existing in the formations penetrated. The pressure exerted against the borehole wall depends on the height of the fluid column and the weight of the drilling fluid. If water is permitted to flow into the well bore from the penetrated formations, sloughing of the hole may occur, resulting in lost time and increased driving costs.

Drilling fluids should prevent formation clays from expanding into the borehole during drilling. Some hydrating clays can absorb large volumes of water, thereby increasing the physical dimensions of the clay. To control this problem, the drilling fluid must isolate formation clays from the water in the drilling fluid. This is usually achieved by adding certain chemicals such as potassium chloride to water-based drilling fluids that contain clay additives, or by using polymeric drilling fluid additives which coat the formation clays and minimize swelling caused by hydration.
3. Cool and lubricate the drill bit. Fluids circulating through the drill string cool and lubricate the bit, thereby avoiding unnecessary bit wear and reducing maintenance.

4. Control fluid loss. All water-based drilling fluid systems must control drilling fluid loss in highly permeable formations by creating a nearly impermeable clay filter cake or polymeric film on the borehole wall. Insufficient filter cake or polymeric film deposition may allow excessive fluid loss or even complete loss of circulation.

5. Drop cuttings into a sealing pit. As the drilling fluid is circulated through the sealing pit, cuttings should drop out so they are not recirculated. The gel strength of the drilling fluid is the primary factor controlling the rate of settlement. Gel strength is a measure of the fluid's ability to suspend cuttings when the fluid is at rest. The flow rate in the settling pit is also important and is controlled by the shape and size of the settling pit.

6. Facilitate acquisition of information about the formation being penetrated. Drilling fluid systems should facilitate the recovery of representative cuttings and permit accurate geophysical logging of the well.

7. Suspend cuttings in the borehole when the drilling fluid is not being circulated. During the time the drilling fluid is not in motion, cuttings tend to settle in the borehole. If the rate of settlement is excessive, cuttings may settle around the drill bit or stabilizer and jam the rotation of the drill string when drilling is resumed.

During drilling, the principal objective is to maintain the drilling fluid in a suitable condition in spite of changing downhole or surface conditions and the continuous addition of suspended drill cuttings. In most cases, continuous monitoring of the drilling fluid is necessary to achieve the best results.

5.3. PROPERTIES OF WATER-BASED DRILLING FLUIDS

The drilling fluid properties listed in Table 5.2 should be understood thoroughly by the drilling contractor. Regardless of which drilling fluid system is used, its effectiveness will depend upon the contractor's ability to anticipate the chemical and physical changes taking place during drilling and to make modifications as required. At a minimum, all rotary drilling crews should be able to measure drilling fluid density and viscosity, and understand the relationship of these properties to hole stability, cuttings removal and fluid-loss control. The physical and chemical behavior of bentonite and polymers differs significantly. These differences are examined separately as each drilling fluid property is discussed below.

<table>
<thead>
<tr>
<th>1. Density (weight)</th>
<th>4. Gel strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Viscosity</td>
<td>5. Fluid-loss-control effectiveness</td>
</tr>
<tr>
<td>3. Yield point</td>
<td>6. Luricicy (lubrication capacity)</td>
</tr>
</tbody>
</table>

**Table 5.2. Principal Properties of Water-Based Drilling Fluids**

5.3.1. Density

Control of drilling fluid density is a fundamental factor in successful well drilling. Density is defined as the weight per unit volume of fluid. Thus, the terms density and weight can be used interchangeably. In
the English system, density is expressed in pounds per gallon (lb/gal) or pounds per cubic foot (lb/ft³). The actual pressure exerted at any point in a borehole by a static drilling fluid depends on the fluid density and the height of the fluid column above that point. Specific gravity is another way to express the density of a drilling fluid. It is the ratio of the weight of a given volume of drilling fluid compared with the weight of an equal volume of water. Drilling fluid density is measured easily with a balance scale.

Selection and maintenance of proper drilling fluid density prevents collapse of the hole and flow of water into the borehole. To maintain an open borehole, the pressure exerted by the drilling fluid column must exceed the pore pressure (water and gas) in the aquifer. Typically, a minimum excess pressure of 5 psi is desirable, although this pressure requirement may be higher when pressures from confined formations are encountered.

The drilling contractor should be able to calculate the downhole pressures exerted by the drilling fluid at rest to determine whether the hydrostatic pressure is sufficient to control the pore pressure in the formation. A simple equation for determining the hydrostatic pressure exerted by the drilling fluid in a borehole is given by

\[
\text{Hydrostatic pressure} = \text{fluid density} \times \text{height of fluid column} \times 0.052
\]

where hydrostatic pressure is in psi, density in lb/gal and height in ft.

Under most drilling conditions, the hydrostatic pressure exerted by the weight of the drilling fluid column above the static water level in the borehole is sufficient to create positive pressures in the borehole; that is, the hydrostatic pressure created by the drilling fluid is great enough to keep the borehole open (Figure 7.1). When static water levels are high, however, the weight of the drilling fluid column above the static water level may not be sufficient to keep the borehole open.
Under ordinary conditions, the maximum density that can occur in a clay system as a result of the entrainment of solids during drilling is about 11 lb/gal. Further increases in density while maintaining a proper solids/fluid ratio requires the introduction of higher density material so that less solids by volume are needed for a specific density. Barite, with a specific gravity of 4.2 to 4.35, is a standard weighting material and is much heavier than clay additives and most formation materials, which have specific gravities of 2.6 to 2.7. Barite particles are sized so as to remain suspended in the drilling fluid, but are not small enough to affect the flow characteristics of the fluid.

To control the flow of water into the borehole, the contractor should increase the density of the drilling fluid before reaching the confined formation. The additional drilling fluid density required to equalize the confined pressure is determined by:

\[
\text{Drilling fluid density} = \text{weight of water} \cdot \frac{\text{height of water above-ground level} \cdot \text{depth to top of confined aquifer}}{\text{height of water above-ground level}}
\]

The calculated drilling fluid density will only balance the confined pressure, however, and thus a safety factor of 0.3 lb/gal is usually recommended. The total added density should be enough to control any potential collapse of the formation during circulation of the drilling fluid and withdrawal of the drill pipe.
During the drilling process, solids generally begin to accumulate in the drilling fluid, causing the density to increase. If silt, clay, or weakly consolidated shale is present, the density increase may be significant and water must be added or solids removed to reduce the solids/fluid ratio. Too great an increase in density can affect the drilling and well completion processes in the following ways:

- Large volumes of drilling fluid and cuttings can be forced into the aquifer during drilling. Removal of the drilling fluid and cuttings during development can be extremely difficult, especially if clay additives are used.

- Material costs increase because of high fluid losses, particularly in areas where mix water is expensive or must be hauled long distances.

- Rate of penetration is reduced.

- Sample collection is more difficult and less reliable because cuttings do not drop out of the drilling fluid at the surface.

- Wear on a mud pump is increased because it must keep recirculating the high volume of unnecessary solids.

- Pumping costs increase because solids are continually recirculated.

5.3.2. Flow Characteristics of Drilling Fluids

The flow characteristics of a drilling fluid—viscosity, gel strength, and yield point—depend primarily on the size, shape, and molecular structure of the particles in the fluid. Clay particles are less than 4 microns in size, silt and barite are 4 to 63 microns, and fine to medium sand is 63 to 500 microns. The silt, and barite if present, provide mainly density, whereas the clay particles enhance the viscosity and filtration characteristics as described below. Polymeric particles are usually much smaller than clay. For example, finely ground polymeric particles made from guar seeds are about 0.0001 micron in size. The addition of even small volumes of polymers to a drilling fluid can have a significant effect on viscosity.

Particle shape is important in determining how a fluid flows. Flat, tabular particles have large surface areas for their sizes and can “tie up” relatively large volumes of water. Some small particles, such as clay colloids, possess powerful electrical charges that affect the fluid both while it is in motion and at rest. In contrast, polymeric particles have a long-chained molecular structure that causes distinctive changes in the flow characteristics of a drilling fluid, depending on the amount of stress applied at various points in the circulation system.

5.3.3. Viscosity

Viscosity is the resistance offered by a fluid to flow, or, in this case, to being pumped. It has no relationship to density and is measured in different units. The viscosity and uphole velocity are the primary factors determining the ability of a drilling fluid to remove cuttings from around the bit and move them up the borehole. The viscosity of any drilling fluid depends on many factors: (1) viscosity of the base fluid used, (2) number of particles (solids) per unit volume of drilling fluid, (3) density, size, and shape of particles, and (4) the attracting or repelling forces between the solid particles and between the solids and the base fluid (hydration potential). In general, high viscosity drilling fluids are required to lift coarse sand or gravel, whereas lower viscosity drilling fluids are adequate to lift fine sand and silt.
Viscosity of a fluid can be measured by a viscometer or a Marsh funnel. A certain volume of drilling fluid is allowed to drain from a special funnel into a cup; the flow time is recorded and calibrated against the time required for an equal volume of water to drain from the funnel (about 26 seconds at 70°F). These values, called apparent viscosities, are approximate and are good only in a relative sense.

Viscosities should be no higher than necessary to efficiently lift cuttings to the surface and control fluid losses. Although drilling conditions can vary greatly, a Marsh funnel viscosity of 35 to 40 seconds will usually be satisfactory in fine sand formations. If coarse sediment (gravel) is encountered, viscosities must be substantially increased so that coarser particles do not have to be finely ground to be lifted by the drilling fluid.

5.3.3.1. Viscosity of Drilling Fluids Made with Clay Additives

The viscous nature of drilling fluids made with clay additives originates from the small size of clay particles (less than 4 microns) and their relatively large surface areas. Most clay particles have a platelike structure; groups of these platelets are common. Clay particles generally swell when exposed to water because the electrically unbalanced water molecules are strongly attracted to the plate surfaces and thereby force the plates apart. This results in the clay particles occupying a larger space, which leads to a more viscous fluid. Different types of clay have a wide range of hydration potential. Clays that hydrate effectively are preferred because they produce a low-solids drilling fluid with high viscosity. Clays such as montmorillonite, kaolinite, and illite are the primary clays used for fresh-water drilling fluids, although montmorillonite is the only clay of these three that is available commercially. The viscosity-building characteristics of sodium montmorillonite are the greatest of any clays, because the sheets of atoms making up the flat clay particles are much thinner and come apart more easily in water than those of other clays. Clays used for drilling fluids are rated by their yield, which is defined as the number of 42-gallon barrels of drilling fluid with an apparent viscosity of 15 centipoise produced by 2,000 lb of clay. Water at 68°F has a viscosity of 1.005 centipoise. The term “bentonite” is used as a commercial name for clays that are predominantly sodium montmorillonite. Wyoming bentonite is most common drilling fluid additive used in the water well industry.

<table>
<thead>
<tr>
<th>Material Drilled</th>
<th>Appropriate Marsh Funnel Viscosity (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine sand</td>
<td>35 - 45</td>
</tr>
<tr>
<td>Medium sand</td>
<td>45 - 55</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>55 - 65</td>
</tr>
<tr>
<td>Gravel</td>
<td>65 - 75</td>
</tr>
<tr>
<td>Coarse gravel</td>
<td>75 - 85</td>
</tr>
</tbody>
</table>

Table 5.3. Approximate Marsh Funnel Viscosities Required for Drilling in Typical Types of Unconsolidated Materials

5.3.3.2. Viscosity of Drilling Fluids Made with Polymeric Additives

In recent years, the use of natural and synthetic polymeric colloids in drilling fluids has increased. A polymer is a long-chained chemical compound consisting of many small molecular units (monomers) combined together. Polymers can be either natural or synthetic, usually have a high molecular weight, and form chains of monomers several thousand units long. When the chains become tangled, they tend to
make a strong film. Polymers may be used as the primary additive or to beneficiate bentonitic drilling fluids. They are described as low-solids or clay-free drilling fluid additives. Polymers are used to increase drilling rates and drilling fluid yields, thereby decreasing operational costs.

The unusual physical and chemical properties of polymers offer several specific advantages: (1) holes can be drilled with reduced bottom-hole pressures; (2) fluid loss can be controlled without the buildup of a thick filter cake; (3) torque and friction losses are reduced; (4) cores and other samples are not masked by the drilling fluid additive; (5) some polymers are compatible with brackish water or even brine; and (6) cuttings settle rapidly at the surface so it is possible to circulate clean, lightweight, nonabrasive fluids. Polymers also increase the effectiveness of some well-logging methods because of their high resistivity.

5.3.4. Gel Strength of Drilling Fluids Made with Clay Additives

Gel strength is a measure of a drilling fluid's ability to support suspended particles when the fluid is at rest. The gel structure of a drilling fluid made with clay additives is produced when the clay platelets align themselves to join together positive and negative charges. The positively charged edge of a plate aligns itself with the negatively charged flat surface of an adjacent plate. This structure gives the liquid a plastic form with strength properties caned gel strength. If enough stress (agitation) is applied to the drilling fluid by the pump, the gel will break down.

When a drilling fluid is at rest, however, some of the clay plates will orient themselves to balance the electrical charges on the edges and flat surfaces of the plates. This process is called flocculation and is the main cause of gel strength.

A drilling fluid generally exhibits more than one physical condition. The four common drilling fluid states are aggregated-flocculated, aggregated-deflocculated, dispersed-flocculated, and dispersed-deflocculated. The greatest gel strength occurs when the drilling fluid is in a dispersed-flocculated state. For example, if the driller has done a thorough job of mixing the clay additives so the platelets are dispersed, and the drilling fluid is then allowed to remain at rest, the drilling fluid will assume a dispersed-flocculated state leading to a high gel strength and a uniform solids content.

If a drilling fluid with clay additives is left standing in a borehole or mud pit for some time, it gains in gel strength as increasing numbers of clay plates align themselves. This quality is called thixotropy and is a characteristic of rainy paints and varnishes. After the drilling fluid has been allowed to remain at rest for some time, excessively high gel strengths may demand so much pump pressure to resume circulation that the drilling fluid may be forced into fractured or weak formations.

Adding bentonite win increase gel strength, but care must be taken not to add so much that settlement of cuttings at the surface is retarded. Just enough bentonite should be used to lift the cuttings and support any weighting material at the desired pumping rate.

Water chemistry also affects the gel strength of a drilling fluid made with clay additives. The use of soft water helps clay additives attain a well flocculated condition, whereas in hard water groups of clay platelets tend to remain together and gel strengths are somewhat less.

5.3.5. Gel Strength of Drilling Fluids Made with Polymeric Additives
Natural and synthetic polymeric drilling fluids have virtually no gel strength. This lack of gel strength assures that cuttings removal is exceptionally good at the surface, wear on the mud pump by abrasive material is minimized, and pumping pressures are minimized during normal circulation and resumption of circulation. The drilling contractor should, however, clear the borehole of cuttings before circulation is stopped, to prevent them from accumulating around the drill bit.

5.3.6. Filtration

Another of the principal requirements for a drilling fluid is to prevent fluid loss by forming a filter cake or low-permeability film on the porous face of the borehole. The sealing property depends on the amount and nature of the colloidal materials in the drilling fluid. The filter cake produced by clays and the thin film created by polymeric colloids are physically dissimilar, because the size and shape of the particles differ and their ability to hydrate is significantly different. Colloidal particles and suspended cuttings entrained during drilling are important components of the total solids that create a filter cake or film. Thus, the filtration properties of all drilling fluids are, in part, supplied by materials derived from the borehole.

When drilling begins, hydrostatic pressure in the borehole causes the drilling fluid to flow into porous formations. For drilling fluids made with clay additives, the fluid and some clay particles initially enter the formation unhindered; but as the suspended solids and cuttings continue to close off the pores, clay particles filter out and form a cake on the borehole wall. As the remaining pores around the borehole become clogged with particles, progressively smaller volumes of water can pass into the formation (Figure 5.2). In time, a filter cake effectively limits water flow through the borehole wall except in highly permeable zones where lost circulation is apt to occur.

During drilling, the thickness of the clay filter cake will vary according to the rate of erosion caused by the rotation of the tools and by the uphole velocity of the drilling fluid. In addition, thicker filter cakes will form in formations that have higher hydraulic conductivity. When circulation stops, the filter cake will continue to build up on the wall of the borehole.

The nature of this filter cake or film and the way it forms are quite different when drilling fluids are prepared with polymers. Guar gum is a polysaccharide that provides natural fluid-loss control. This property is derived from both the soluble guar gum particles (sols) dispersed in the drilling fluid and the insoluble cell-wall residue (insols) of the gum.
Although a filter cake is required during drilling, any residual clays on the borehole wall and in the aquifer after the well has been completed are highly detrimental to the well's productivity. Well development procedures should be conducted as soon as possible after a well has been drilled. Otherwise, complete drilling fluid removal may become impossible, especially if clay additives are used. Filter cake removal during development can be accomplished primarily by mechanical means, even though the addition of polyphosphates can be helpful.

5.3.7. Design of Mud Pits

Drilling fluid is usually mixed adjacent to the drilling rig in either portable or excavated pits. The capacity of portable pits for direct rotary rigs ranges from 200 to 10,000 gal. Large pits, 20,000 to 80,000 gal, are suitable for reverse circulation drilling. Although a mud pit is excavated prior to drilling with reverse circulation, a premixed drilling fluid is usually not prepared because only clean water is generally used. The size of the mud pit is dictated by the volume of drilling fluid contained in the finished borehole and the need for a reserve volume, which varies according to the particular rotary system used. Usually the volume of the pit is one and a half to three times the volume of the finished hole. For reverse rotary drilling, where drilling fluid losses are usually high, the volume of the pit is generally three times the volume of the finished borehole.

The design of the mud pit should take several factors into consideration (Figure 5.3). The principal objectives of the pit are to store an adequate volume of drilling fluid and to act as an effective settling basin for suspended cuttings. For efficient removal of the suspended cuttings, the pit should be constructed in two sections—the settlement part and the suction part.
Many drillers, however, use single-reservoir pits that serve both of these functions. The velocity of the drilling fluid as it moves through the mud pit during the storage interval must be as low as possible. This can be achieved by changing the direction of flow as the drilling fluid moves through the pits, as well as by deepening part of the pit or by using baffles and overflows. Deeper, rather than wider, trenches are more satisfactory in reducing drilling fluid velocity. When a single pit is used, some drillers will slope the bottom of the pit downward toward the pump suction point to slow the velocity and create a place for the cuttings to settle. The suction hose must be mounted above the bottom of the pit. The bottom of an excavated mud pit should be sealed with a plastic film or a compacted layer of clay.

5.4. AIR DRILLING

Many water wells are now drilled with air because of the relative simplicity and effectiveness of air systems and the increasing number of rotary rigs equipped with air compressors. The earliest attempts to use air as a circulating medium during the 1950's showed that significant increases in penetration rates and bit life could be obtained. Air drilling is now recognized as a primary method to reduce drilling time and therefore the cost of a well. The mechanics of air drilling are more difficult to understand than typical water-based systems because the drilling fluid is compressible and often contains water, an incompressible fluid, and other special additives.

To drill with air, the drilling rig must have access to an adequately sized compressor and a water pump that can inject up to 10 gal of water and chemicals into the air stream. On some rigs, a special pump is used to inject surfactants into water before the water is injected into the drill rods.
The compressor is usually the key to successful air drilling because insufficient air volume and pressure are the principal problems in air drilling.

Compressors used on water well rigs are either the piston (reciprocating) type or the helical-screw type. Piston-type compressors are efficient at compressions up to 30:1 and possess high pressure capacity. On the other hand, screw-type compressors typically have somewhat lower pressure capacity than piston compressors, but are positive displacement and consequently produce a constant air volume.

Compressors are rated to deliver a given air volume at a certain operating pressure. In practice, air delivery at a rated pressure means that a specific number of cubic feet of air at atmospheric pressure can be compressed and delivered to the rig at that pressure every minute. Once the air has been compressed to the delivery pressure, it no longer has the original free-air volume. The compressor rating is valid at sea level (maximum air density) at an air temperature of 60°F. The rating is usually designated at a compressor speed of 1,800 to 2,100 rpm. As atmospheric pressure decreases or temperature increases above 60°F, less standard air volume is compressed at a given rpm.

Both piston compressors and screw-type compressors can have one or more stages (compression units). Air volume or pressure demands often require that more than one compressor be used. Compressors connected in series will increase the pressure in an air system, whereas a parallel arrangement will increase the volume. Although the output pressure can be regulated on a screw compressor, it should never be reduced when a down-the-hole air hammer is being used in air drilling. The pressure may be adjusted downward for well development work, however, so the screen is not damaged. This is especially important if the pressure is greater than 300 psi.

The standard compressors used on water well rigs have increased in air-volume capacity and pressure capability in order to drill deep, large-diameter holes, to achieve high penetration rates, and to maximize drilling rates with down-the-hole hammers. A good method to verify that enough air is available to remove the cuttings efficiently in dry-air drilling is to check the time needed for the air to clean up after drilling ceases. The time required to clean the cuttings should not greatly exceed 6 to 7 seconds per 100 ft of borehole. More air is needed as boreholes deepen, in addition, 30 to 40 percent more air is required when drilling with air-mist systems.

For down-the-hole air hammers, higher pressures translate into increased penetration rates when drilling with dry air because the hammer action is more rapid. Higher available pressure can also be used to overcome static heads following a temporary cessation of drilling.

Several options exist when air is used as the drilling fluid:

1. Air alone (dry air)

2. Air mist—a. Air plus a small volume of water b. Air, small volume of water, plus a small amount of surfactant

3. Air-foam--- a. Stable foam—air plus surfactant b. Stiff foam—air, surfactant, plus high-molecular-weight polymer or bentonite

4. Aerated mud---water-based drilling fluid plus air
Decisions on which of these systems to use depend on the volume of water entering the borehole, the penetration rate, the volume of air available, the nature of die formations being drilled, and environmental conditions affecting the drilling process.

5.4.1. Dry-Air Systems

The simplest air drilling system involves using only dry air as the drilling fluid. Optimum drilling rates are achieved by using dry air because the column of air puts minimum pressure on the bottom of the borehole. As removal of the rock overburden proceeds, the cuttings become progressively easier to chip off because the overlying weight of the rock has been removed. Water well drillers will ordinarily begin all boreholes with only dry air, but dust problems and influx water will usually create the need to alter the dry-air system.

Compared with water-based drilling fluids, dry-air systems offer the following advantages:

1. Higher penetration rates in dense, consolidated rock
2. Reduced bit wear
3. High solids-carrying capacity
4. Reduced formation damage and self-induced fluid loss
5. Low water requirements
6. Minimized swelling problems associated with water-sensitive clays

Air drilling is extremely effective in drilling hard, stable formations such as igneous and metamorphic rocks, and tough, dense sedimentary rocks such as dolomite where penetration rates are often exceptional. Because air has the lowest density of any drilling fluid and therefore places minimum downward pressure on the formation being drilled, cuttings chip off readily with either a roller or a down-the-hole air hammer bit. Boreholes are kept clean by the high annular fluid velocity, which ranges from 3,000 to 5,000 ft/min for dry air. Up-hole velocities to 7000 ft/min may be desirable for deep holes drilled at high penetration rates. In general, the lifting capacity of air is proportional to its density and to the square of its annular velocity. Thus, the driller adjusts air volume and pressure at the surface to compensate for the weight of the cuttings and for increases in density with depth in order to maintain the required annular velocity.

Air drilling is particularly advantageous where drill and drive techniques are used for unconsolidated formations such as glacial outwash and alluvial deposits or for semiconsolidated formations such as bouldery tills. In this type of drilling, hole stability is not a major problem and the many benefits of drilling with air make this technique attractive.

Air is helpful in overcoming lost-circulation problems in highly fractured igneous and metamorphic rock and in highly porous formations. Many drillers who use water-based drilling fluid systems will change immediately to an air or air-foam system if large crevices or cavities are encountered. However, lost-circulation problems can occur when air systems are used to drill permeable sandstone. In this type of formation, so much air is lost that up-hole velocities may be insufficient to lift the cuttings. To overcome this problem in sandstone, polymers and water are sometimes added to the air. The thin polymeric film seals the formation pores so air loss is minimized.

Problems with air drilling, especially dry-air drilling, usually involve an insufficient air supply, resulting in an annular velocity that is not high enough to carry the cuttings to the surface. For a given diameter, hole depth is a primary factor affecting cuttings removal because air-volume requirements are directly
related to depth. Erosion of the borehole walls can also create an increase in the demand for air that may exceed the capacity of the compressor. On the other hand, too much air can be a problem because soft spots in a borehole wall can be eroded, resulting in blowouts (borehole enlargement) which, in turn, can lead to even higher air-volume demands.

Another drilling problem occurs when small amounts of water begin to enter the borehole during dry-air drilling. Water mixes with the smallest rock cuttings to produce muds that can plug the formation and limit the potential yield of the well. If enough mud is present to form rings, or collars, on the drill string or borehole wall, air flow is restricted and the drill rods may stick in the borehole. When mud collars form, restriction of the annulus causes excessive pressure build up below the collar, and fracturing of the formation materials can occur. Fracturing and blowouts can be minimized if the rig is equipped with compressors that can be controlled by a relief valve at the operator’s station. The driller can then take immediate action when the pressure rises suddenly to reduce the chance for blowouts and fracturing in loose formations.

5.4.2. Air-Mist Systems

Adding small amounts of water to air creates an air-mist system. Many drillers add water to the air system to control dust and to help break down any mud collars forming on the drill muds. To help increase the wetting action of the injected water, small amounts of surfactant may also be added to the airstream. Air-volume requirements usually increase substantially when switching from dry air to air misting, because greater downhole pressure prevents immediate expansion of the air as it leaves the bit. Air-mist techniques can be used satisfactorily as long as only small volumes of influx water, 15 to 25 gpm, enter the borehole from the aquifer. When the volume of water entering the borehole increases, an air-foam system must replace the mist system.

5.4.3. Air-Foam Systems

Ordinarily, foam is defined as a dispersion of air in water. In an air-foam drilling system, however, air is the continuous phase and water is the dispersed or discontinuous phase. Thus, drilling foam is created when a small volume of water and surfacing is injected into an airstream. Although some foam forms naturally when water enters an airstream, the amount and stability of the foam is enhanced significantly when a surfactant is added. The term "foam drilling" is associated with the introduction, into air, of a surfactant mixed with water. Surfactants include anionic soaps, alkyl polyoxethylene nonionic compounds, and cationic amine derivatives. All of these are available as commercial products.

The addition of a surfactant to an air-based drilling fluid has several advantages over the use of air alone. These include:

1. Higher solids-carrying capacity
2. Ability to lift large volumes of water
3. Reduced air-volume requirements
4. Reduced erosion of poorly consolidated formations
5. Effective dust suppression
6. Increased borehole stability

Air-foam systems are not effective, however, when confined formations are intercepted, because the downhole pressure is so low that the borehole may become unstable or so much water may enter the borehole that the air-foam system cannot remove it.
Foams are used primarily to enhance the rate of cuttings removal by preventing them from aggregating so they can be lifted more easily to the surface. Foaming agents are also added to air when the airstream can no longer lift the water entering the borehole. The required volume of surfactant will usually range from 1 qt to 3 gal per hour, depending on the type of surfactant, the volume of water entering the borehole, the diameter and depth of the borehole, and the quantity and size of the cuttings. The surfactant concentration commonly varies from 0.25 to 2 percent of the injected water, but may be increased significantly in deep, large diameter boreholes with large quantities of influx water.

5.4.4. Aerated Drilling Fluids

Air is sometimes injected into water-based drilling fluids to lighten the weight of the drilling fluid column. This procedure is common in the Inverse system and for air-assist reverse-circulation rotary drilling. The introduction of air increases the penetration rates 10 to 50 percent over conventional mud drilling. In addition, fluid loss to highly permeable zones is often reduced or eliminated. One disadvantage of aerating water-based drilling fluids is that it causes higher rates of drill-pipe corrosion.

5.4.5. Regulating the Air-Foam Drilling System

In most air-foam drilling operations, the contractor will have an intuitive feeling as to whether the drilling fluid system is functioning properly, mainly on the basis of penetration rate. But just as in water-based drilling fluid systems, adjustments of the physical characteristics of the drilling fluid should be based on more than just intuition if maximum drilling efficiency is to be maintained. Because conditions change as the drilling fluid circulates in the system, the required pressure, air volume, and liquid-volume fraction (LVF) normally should be established for the most critical point—in the annulus just above the bit. At this point, the LVF should be 2 to 5 percent; in no case should it be more than 15 percent.

Unfortunately, it is rarely possible to actually measure pressure or temperature conditions at many points in the circulation system. Therefore, the driller must observe (usually at the discharge point) various physical characteristics of the air-foam system when possible and learn to relate these characteristics to drilling efficiency. The important visual observations or measurements which indicate when the adjustments should be made are listed below.

1. Water volume, air volume, and pressure.
2. Foam pressure at the standpipe.
3. Percentage of surfactant and other foam stabilizers being injected.
4. Foam consistency at the surface:
   a. Visual assessment for consistency
   b. Density
   c. Percent LVF
   d. Percent and size of solids
   e. Volume
5. Regularity of returns at the surface.
6. Drill-string torque requirements.

As a general operating guide for an air-foam system, the driller should attempt to maintain foam consistency once the rates of penetration and water removal are satisfactory. The ability to make the correct adjustments to the system by visual observations and actual measurements will improve as the
experience and skill of the contractor increases. When initiating an air-foam system, the driller will generally observe the following:

1. Before the foam has become stable downhole, a steady rush of air will leave the discharge tee. If the foam does not form, fluid (injection) volume should be increased or air volume decreased for a few minutes.
2. When the proper foaming action begins downhole, a gentle puffing of air can be felt at the discharge tee.
3. When foam returns begin, the foam should extrude steadily and have good stiffness.
4. Good foam-carrying capacity usually occurs when a gentle surging action is observed at the discharge tee. If the foam is too stiff, this surging action will not occur. If the foam surges violently, too much air is being pumped into the borehole.
5. As conditions change, the proper foam concentration, water injection rate, and air volume must be maintained to achieve good penetration.

Common problems with foam drilling fluids are indicated by the physical condition of the foam at the surface and by pressure buildup in the borehole.

In summary, specific suggestions for successful air-foam drilling include the following:

1. The greatest lifting capacity occurs when the LVF is about 2 percent, therefore, the LVF at the bottom of the borehole should be as close to 2 percent as possible. If the LVF exceeds 25 percent, the lifting capacity of the foam will be unsatisfactory.
2. The annular velocity at the bottom of the borehole should be at least 50 ft/min.
3. To calculate the correct volume of water to be injected for an LVF of 2 percent and an uphole velocity of 100 ft/min, multiply the annular volume for 1 ft of borehole by 2. Another good rule of thumb is to inject at a rate of 0.5 to 1 gpm per 1 in of borehole diameter.
4. For most shallow water wells, 50 to 500 cfm of air are needed at pressures of 100 to 350 psi.
5. A safety factor for calculated air volume is usually 25 percent.
6. A temperature correction for air-volume changes may be necessary, but for most drilling operations the temperature change is not sufficient to necessitate a correction.

5.5. DRILLING FLUID ADDITIVES

A proliferation of drilling fluid additives has occurred since 1940. For most water well drilling operations, certain standard procedures are followed which depend on the particular type of drilling fluid used. Specific ranges for viscosities, uphole velocities, and additive concentrations are well established and represent the starting point for mixing most drilling fluids. However, unusual borehole structure or groundwater chemistry may dictate a change from these initial drilling fluid conditions.

5.6. GUIDELINES FOR SOLVING SPECIFIC DRILLING FLUID PROBLEMS
The enormous variety of chemical and physical conditions that can exist in boreholes, and the large number of commercial products available to remedy specific problems, preclude a simple prescription for successful use of drilling fluids. Certain problems, however, occur regularly in typical geologic formations when using ordinary additives. Swelling clays, for example, are a major problem when drilling with rotary systems. The Corcoran Clay in the San Joaquin Valley of California, and the Laramie Formation in the Denver Basin, are notable examples. As the clays hydrate and expand, the borehole is partially or completely plugged, and occasionally the drill string may become stuck. The section below contains recommendations for solving clay swelling and other common drilling fluid problems.

**PROBLEM:** Inadequate cuttings removal from borehole.

**RECOMMENDED ACTION:**

1. Clays and polymeric solids in water.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Reason for Occurrence</th>
<th>Corrective adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air blowing free at the blooey line with a fine mist of foam</td>
<td>Air has broken through foam mix preventing stable foam formation</td>
<td>Increase liquid injection rate or decrease air injection rate</td>
</tr>
<tr>
<td>Foam thin and watery</td>
<td>Formation water entry with possible salts contamination</td>
<td>Increase liquid and air injection rates, and possibly increase percent of foaming agent</td>
</tr>
<tr>
<td>Quick pressure drop</td>
<td>Air broken through foam mix preventing formation of stable foam</td>
<td>Increase liquid injection rate or decrease air injection rate</td>
</tr>
<tr>
<td>Slow, gradual pressure increase</td>
<td>Increase in amount of cuttings or formation fluid being lifted to surface</td>
<td>Increase air injection rate slightly</td>
</tr>
<tr>
<td>Quick pressure increase</td>
<td>Bit plugged or formation packed off around drill pipe</td>
<td>Stop drilling and attempt to regain circulation by moving pipe</td>
</tr>
</tbody>
</table>

**Table 5.4. Common Problems with Air-Foam Systems (After DrilChem)**

The enormous variety of chemical and physical conditions that can exist in boreholes, and the large number of commercial products available to remedy specific problems, preclude a simple prescription for successful use of drilling fluids. Certain problems, however, occur regularly in typical geologic formations when using ordinary additives. Swelling clays, for example, are a major problem when drilling with rotary systems. The Corcoran Clay in the San Joaquin Valley of California, and the Laramie Formation in the Denver Basin, are notable examples. As the clays hydrate and expand, the borehole is partially or completely plugged, and occasionally the drill string may become stuck. The section below contains recommendations for solving clay swelling and other common drilling fluid problems.

**PROBLEM:** Inadequate cuttings removal from borehole.

**RECOMMENDED ACTION:**

1. Clays and polymeric solids in water.
<table>
<thead>
<tr>
<th>Base Fluid</th>
<th>Additive/Concentration</th>
<th>Marsh Funnel Viscosity (seconds)</th>
<th>Annular Uplike Velocity (ft/min)</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>None</td>
<td>26 ± 0.5</td>
<td>100 - 120</td>
<td>For normal drilling (sand, silt, and clay).</td>
</tr>
<tr>
<td>Water</td>
<td>Clay (High-Grade Bentonite)</td>
<td>15-2 lb/100 gal</td>
<td>35 - 55</td>
<td>80 - 120</td>
</tr>
<tr>
<td>Water</td>
<td>Clay (High-Grade Bentonite)</td>
<td>25-40 lb/100 gal</td>
<td>55 - 70</td>
<td>80 - 120</td>
</tr>
<tr>
<td>Water</td>
<td>Clay (High-Grade Bentonite)</td>
<td>35-45 lb/100 gal</td>
<td>65 - 75</td>
<td>80 - 120</td>
</tr>
<tr>
<td>Water</td>
<td>Polymer (Natural)</td>
<td>4.0 lb/100 gal</td>
<td>35 - 55</td>
<td>80 - 120</td>
</tr>
<tr>
<td>Water</td>
<td>Polymer (Natural)</td>
<td>6.1 lb/100 gal</td>
<td>65 - 75</td>
<td>80 - 120</td>
</tr>
<tr>
<td>Water</td>
<td>Polymer (Natural)</td>
<td>6.5 lb/100 gal</td>
<td>75 - 85</td>
<td>80 - 120</td>
</tr>
<tr>
<td>Air</td>
<td>None</td>
<td>N/A</td>
<td>3,000 - 5,000</td>
<td>Fast drilling and adequate cleaning of medium to fine cuttings, but may be dust problems at the surface.</td>
</tr>
<tr>
<td>Air</td>
<td>Water (Air Mist)</td>
<td>0.25-2 gpm</td>
<td>N/A</td>
<td>4,500 - 6,000</td>
</tr>
<tr>
<td>Air</td>
<td>Surfactant/Water (Air-Foam)</td>
<td>1.0-2 gal/100 gal</td>
<td>3,000 - 5,000</td>
<td>Controls dust at the surface and is suitable for formations that have limited entry of water.</td>
</tr>
<tr>
<td>Air</td>
<td>Surfactant/Water (Air-Foam)</td>
<td>0.25-0.5% surfactant</td>
<td>N/A</td>
<td>50-1,000</td>
</tr>
<tr>
<td>Air</td>
<td>Surfactant/Colloids/Water (Stiff Foam)</td>
<td>3.4 qt/100 gal (0.75-1% surfactant)</td>
<td>N/A</td>
<td>50 - 100</td>
</tr>
</tbody>
</table>

(Compiled partly from information presented in Imco Services, 1975; Magocbar, 1977; and Buron, 1968.)

Table 5.5. Typical Additive Concentrations, Resulting Viscosities, and Required Uplike Velocities for Major Types of Drilling Fluids Used in Various Aquifer Materials
a. Increase uphole velocity of the drilling fluid
b. Increase viscosity of the drilling fluid by adding more colloidal material
c. Increase density of the drilling fluid by adding weighting material
d. Reduce penetration rate to limit cuttings load.

2. Air
   a. Increase uphole velocity of fluid system by adding air or water
   b. Add surfactant to produce foam or to increase concentration of surfactant
   c. Decrease air injection rate if air is breaking through the foam mix and preventing formation of stable foam
   d. Decrease water content of the foam system

PROBLEM: The rate at which cuttings will drop out is too low because the inadvertent addition of native clays during drilling has produced excessive viscosity in the drilling fluid

RECOMMENDED ACTION:
1. Add water to dilute the drilling fluid
2. Add commercial thinner to reduce the addictive forces between clay colloids
3. If using clay additives, convert to a polymeric system.
4. Separate the solids from a clay additive system with shale shakers and desanders connected in series, or a shale shaker alone. Utilization of a desander or shale shaker may be unnecessary when a polymeric system is being used.
5. Redesign or clean the pit system to increase rate of cuttings settlement.

PROBLEM: Gel strength becomes too great because of strong flocculation, high concentration of solids, or contamination from evaporite deposits or cement. (Excessive gel-strength problems do not occur with polymeric colloids.)

RECOMMENDED ACTION:
1. Add water to dilute the drilling fluid.
2. Add polyphosphate or commercial thinner to reduce electrical charges between clay colloids.
3. Use desander or shale shaker to remove solids from a clay additive system.
4. Lower the pH.

PROBLEM: Excessive fluid loss into the formation, causing thick filter cakes that can produce tight places in the hole, development problems, formation (clay) sloughing, and misinterpretation of electric or gamma-ray logs.

RECOMMENDED ACTION:
1. Increase viscosity by adding bentonite or polymeric colloids to any waterbased system.
2. Add commercial viscosifiers such as CMC or HEC.
3. Reduce density of the drilling fluid.
4. Prevent drastic changes in downhole pressures and maintain downhole pressures at a minimum.

Suggestions include:
   a. Raise and lower the drill string slowly.
   b. Drill through any tight section; do not spud.
c. Begin rotation of the drill pipe, and then start the pump at a low rate and gradually increase the rate.
d. Operate the pump at the lowest rate that will assure adequate cooling of the bit and removal of cuttings from the bit face.
e. Prevent balling at the bit; do not drill soft formations so fast that the annulus becomes overloaded and pressure builds up.

PROBLEM: Lost circulation in permeable formations, faulted and jointed rock, solution cavities in dolomite and limestone, or fractures created by excessive borehole pressures in semiconsolidated or well consolidated rock.

RECOMMENDED ACTION:

1. Reduce density of the drilling fluid system.
2. Switch from a clay additive drilling fluid system to an air-foam fluid, or add surfactant to a dry air system.
3. Gel natural polymeric fluids at the point of fluid loss.
4. Use commercial sealing materials.
5. Drill remainder of the hole with a cable tool rig.
6. Case off, then resume rotary drilling.
7. Kill the borehole with clean sand to the point above lost circulation. Let the material stand in borehole over night. Resume drilling, using low pump pressure.
8. Grout the lost-circulation zone and drill through the plug.

PROBLEM: Confined pressures in the formation.

RECOMMENDED ACTION:

1. Increase density by adding heavy mineral additives such as barite to defiling fluid systems made with clay additives. To suspend barite, the minimum Marsh funnel viscosity must equal four times the final (desired) drilling fluid weight (in lb/gal)
2. Increase density by adding a salt solution to polymeric drilling fluid systems

PROBLEM: Shale sloughing caused by hydration (swelling and dispersion), pore pressures, and overburden pressure.

RECOMMENDED ACTION:

1. Use polymeric additive to isolate water from shale.
2. Maintain constant fluid pressures in the borehole.
3. Minimize uphole velocities.
4. Avoid pressure surges caused by raising or lowering drill rods rapidly.
5. Add 3 to 4 percent potassium chloride (KCl) to water-based systems.
6. Raise the pH of the drilling fluid to stiffen the clay.

PROBLEM: Presence of contaminants. Contaminants usually consist of cement, soluble salts, and gases (hydrogen sulfide and carbon dioxide). Cement in the hole can cause polymeric drilling fluids to break down, thereby inching fluid losses. Salts may cause drilling fluids with clay additives to separate into liquid and solid fractions. Gases in water may affect the physical condition of the drilling fluid.
RECOMMENDED ACTION:

1. For cement problems:
   a. Maintain the pH for natural polymeric drilling fluids at 7 or lower.
   b. Add commercial chemicals such as sodium acid pyrophosphate to drilling fluids with clay additives to restore original viscosity.

2. For salt problems:
   a. Change the clay additive from montmorillonite to attapulgite.
   b. Change to a natural polymeric drilling fluid additive

3. For gas problems:
   a. Add a corrosion inhibitor.

PROBLEM: Drilling at air temperatures significantly below freezing, causing freezeup of the recirculation system.

RECOMMENDED ACTION:

1. Add sodium chloride (NaCl) or calcium chloride (CaCl2) to a natural polymeric drilling fluid. See Table 7.7 for the salt concentrations required to prevent freezing at specific temperatures. Salt must not be added to a dotting fluid made with bentonite.

The problems enumerated above are not the only ones that can occur in water well drilling. Many other problems result from inadequate pumping equipment, particle accumulation in the fluid system and at the bottom of the borehole, slumping or expansion of active shales, and caving of resistant shelflike rocks such as limestone and dolomite. Maintenance of borehole stability and careful drifting procedures can help eliminate these problems, but once they occur, a solution must be determined rapidly for the specific case.

5.7. CONCLUSIONS

This chapter has examined common drilling fluid systems and some typical problems that occur in different geologic materials. Many specific problems associated with drilling can be resolved with the help of the suppliers of drilling fluid products. Many times they can provide in-the-field help, and at least one company sponsors regular training classes in drilling fluid systems. One point should be remembered by the drilling contractor—whatever system you use, understand it well.
<table>
<thead>
<tr>
<th>Initial drilling fluid weight, lb/gal</th>
<th>9.0</th>
<th>9.5</th>
<th>10.0</th>
<th>10.5</th>
<th>11.0</th>
<th>11.5</th>
<th>12.0</th>
<th>12.5</th>
<th>13.0</th>
<th>13.5</th>
<th>14.0</th>
<th>14.5</th>
<th>15.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.0</td>
<td>69</td>
<td>69</td>
<td>69</td>
<td>85</td>
<td>108</td>
<td>128</td>
<td>143</td>
<td>161</td>
<td>171</td>
<td>180</td>
<td>145</td>
<td>120</td>
<td>214</td>
</tr>
<tr>
<td>9.5</td>
<td></td>
<td>69</td>
<td>69</td>
<td>85</td>
<td>108</td>
<td>128</td>
<td>143</td>
<td>161</td>
<td>171</td>
<td>180</td>
<td>145</td>
<td>120</td>
<td>214</td>
</tr>
<tr>
<td>10.0</td>
<td>43</td>
<td>71</td>
<td>145</td>
<td>221</td>
<td>305</td>
<td>390</td>
<td>479</td>
<td>569</td>
<td>667</td>
<td>769</td>
<td>876</td>
<td>876</td>
<td>876</td>
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<tr>
<td>10.5</td>
<td>85</td>
<td>30</td>
<td>74</td>
<td>148</td>
<td>229</td>
<td>312</td>
<td>398</td>
<td>488</td>
<td>583</td>
<td>683</td>
<td>788</td>
<td>788</td>
<td>788</td>
</tr>
<tr>
<td>11.0</td>
<td>128</td>
<td>60</td>
<td>23</td>
<td>74</td>
<td>152</td>
<td>233</td>
<td>319</td>
<td>407</td>
<td>500</td>
<td>598</td>
<td>700</td>
<td>700</td>
<td>700</td>
</tr>
<tr>
<td>11.5</td>
<td>171</td>
<td>90</td>
<td>46</td>
<td>19</td>
<td>76</td>
<td>157</td>
<td>240</td>
<td>326</td>
<td>417</td>
<td>512</td>
<td>614</td>
<td>614</td>
<td>614</td>
</tr>
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<td>12.0</td>
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<td>37</td>
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<td>79</td>
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<td>245</td>
<td>333</td>
<td>426</td>
<td>526</td>
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</tr>
<tr>
<td>12.5</td>
<td>256</td>
<td>150</td>
<td>92</td>
<td>56</td>
<td>32</td>
<td>14</td>
<td>81</td>
<td>162</td>
<td>250</td>
<td>343</td>
<td>438</td>
<td>438</td>
<td>438</td>
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<tr>
<td>13.0</td>
<td>299</td>
<td>180</td>
<td>115</td>
<td>75</td>
<td>48</td>
<td>27</td>
<td>12</td>
<td>81</td>
<td>167</td>
<td>257</td>
<td>350</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>13.5</td>
<td>342</td>
<td>210</td>
<td>138</td>
<td>94</td>
<td>63</td>
<td>41</td>
<td>24</td>
<td>11</td>
<td>83</td>
<td>171</td>
<td>264</td>
<td>264</td>
<td>264</td>
</tr>
<tr>
<td>14.0</td>
<td>385</td>
<td>240</td>
<td>161</td>
<td>112</td>
<td>78</td>
<td>54</td>
<td>36</td>
<td>21</td>
<td>10</td>
<td>86</td>
<td>176</td>
<td>176</td>
<td>176</td>
</tr>
<tr>
<td>14.5</td>
<td>427</td>
<td>270</td>
<td>185</td>
<td>131</td>
<td>95</td>
<td>68</td>
<td>48</td>
<td>32</td>
<td>19</td>
<td>9</td>
<td>88</td>
<td>88</td>
<td>88</td>
</tr>
<tr>
<td>15.0</td>
<td>470</td>
<td>300</td>
<td>208</td>
<td>150</td>
<td>110</td>
<td>82</td>
<td>60</td>
<td>43</td>
<td>29</td>
<td>18</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

The lower left half of this table shows the number of gallons of water which must be added to 100 gal of drilling fluid to produce desired weight reductions. To use this portion of the table, locate the initial drilling fluid weight in the vertical column at the left, then locate the desired drilling fluid weight in the upper horizontal row. The number of gal of water to be added per 100 gal of drilling fluid is read directly across from the initial weight and directly below the desired weight. For example, to reduce an 11 lb/gal drilling fluid to a 9.5 lb/gal drilling fluid, 128 gal of water must be added for every 100 gal of drilling fluid in the system.

The upper right half of this table shows the number of pounds of barite which must be added to 100 gal of drilling fluid to produce desired weight increases. To use this portion of the table, locate the initial drilling fluid weight in the vertical column to the left, then locate the desired drilling fluid weight in the upper horizontal row. The number of pounds of barite to be added per 100 gal of drilling fluid is read directly across from the initial weight and directly below the desired weight. For example, to raise a 9 lb/gal drilling fluid to 10 lb/gal, 140 lb of barite must be added per 100 gal of drilling fluid in the system.

(After Petroleum Extension Service, 1969)
CHAPTER 6.

WELL SCREENS AND METHODS OF SEDIMENT-SIZE ANALYSIS

A well screen is a filtering device that serves as the intake portion of wells constructed in unconsolidated or semiconsolidated aquifers. A screen permits water to enter the well from the saturated aquifer, prevents sediment from entering the well, and serves structurally to support the unconsolidated aquifer material. The importance of a proper well screen cannot be overemphasized when considering the hydraulic efficiency of a well.

Well screens are manufactured from a variety of materials. The value of a screen depends on how effectively it contributes to the success of a well. Important screen criteria and functions include:

1. Criteria
   a. Large percentage of open area
   b. Nonclogging slots
   c. Resistant to corrosion
   d. Sufficient column and collapse strength

2. Functions
   a. Easily developed
   b. Animal incrusting tendency
   c. Low head loss through the screen
   d. Control sand pumping in all types of aquifers

Maximizing each of these criteria in constructing screens is not always possible depending on the actual screen design. For example, the open area of slotted casing cannot exceed 11 to 12 percent or the column strength will be insufficient to support the overlying casing during screen installation. However, open areas of 30 to 50 percent are common for continuous-slot screens with no loss of column strength. In highly corrosive waters, the use of plastic is desirable, but its relatively low strength makes its use impractical for deep wells.

The screen design must accommodate the varying physical and chemical characteristics of ground water. Experience has shown that screens with the following characteristics provide the best service in most geologic conditions and will satisfy the criteria listed above.

1. Slot openings should be continuous around the circumference of the screen, permitting maximum accessibility to the aquifer so that efficient development is possible.

2. Slot openings should be spaced to provide maximum open area consistent with strength requirements to take advantage of the aquifer hydraulic conductivity.

3. Individual slot openings should be V-shaped and widen inward to reduce clogging of the slots and sized to control sand pumping.
4. Screen construction methods should permit the use of a wide variety of materials that are compatible with differing groundwater environments to minimize corrosion and incrustation.

5. If constructed of metal, screens should be of single-metal construction to minimize galvanic corrosion.

6. Screens must be sufficiently strong to withstand stresses normally encountered during and after installation.

6.1. Continuous-Slot Screen

The continuous-slot screen is widely used throughout the world and is the dominant screen type used in the water well industry. It is made by winding cold-rolled wire, approximately triangular in cross section, around a circular array of longitudinal rods. The wire is attached to the rods by welding, producing rigid one-piece units having high strength characteristics at minimum weights. Welded screens are commonly fabricated from Type 304 and Type 316 stainless steel, monel, galvanic or ungalvanized low carbon steel, and thermoplastic materials, mainly PVC and ABS or alloys of these materials.

Slot openings for continuous-slot screens are manufactured by spacing successive turns of the outer wire to produce the desired slot size. These screens are typically fabricated in slot sizes ranging from 0.006 to 0.250 in. Width of the openings can be held to close tolerances in the all welded manufacturing method; allowable variations from the designated (ordered) slot size generally range from 0.001 to 0.002 in, depending on the screen material and screen size. Most high-quality screen manufacturers are concerned with slot variation because sand pumping problems may occur if too many slots are significantly oversized slot control quality is usually checked by comparing the designated size versus the average finished size. All slots should be clean and free of burrs and cuttings.

Slot openings have been designated by numbers which correspond to the width of the openings in thousandths of an inch. A No. 10 slot, for example, is an opening of 0.010 in. Slot size may also be expressed in metric units; for example, 0.010 in equals 0.25 rain. For small-diameter screens covered with wire mesh, the number of openings in the mesh per inch are designated by gauze numbers. The size relationship of slot number and gauze number is shown in Figure 6.1.
For continuous-slot screens, individual slot spacing can be varied during fabrication. In fact, a single section of screen may be made with many different slot sizes if geologic conditions require these variations. In this way, maximum use of the hydraulic conductivity of each stratum is possible.

Each slot opening between adjacent wires is V-shaped, resulting from the special shape of the wire used to form the screen surface. The V-shaped openings, designed to be nonclogging, are narrowest at the outer face and widen inwardly; they allow only two point contact by any sand grains with a diameter larger than the slot size. Thus, oversized particles are retained outside the screen and cannot close off the openings. Any sand grain that will pass through the narrow outer part of the V-shaped opening enters the screen without wedging in the slot. In screens with cut slots without V-shaped design, entering particles often turn or twist sideways and, once lodged in the slots, the available intake area of the screen is considerably reduced, causing either lower yield or greater drawdown (Figure 6.2).

Continuous-slot screens provide more intake area per unit area of screen surface than any other type. For any given slot size, this type of screen has maximum open area Table 6.1 gives representative open areas of venous continuous-slot screens with differing outer wire sizes (face widths) and slot sizes. Note that as the wire face width increases for a given slot size, the open area decreases. However, larger wires increase the collapse strength of the screen for any given diameter.

<table>
<thead>
<tr>
<th>Wire Face Width (mm)</th>
<th>Percent Open Area for Indicated Slot Width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.010 in (0.25 mm)</td>
</tr>
<tr>
<td>0.047</td>
<td>17.5</td>
</tr>
<tr>
<td>0.061</td>
<td>14.1</td>
</tr>
<tr>
<td>0.092</td>
<td>9.8</td>
</tr>
<tr>
<td>0.110</td>
<td>8.3</td>
</tr>
<tr>
<td>0.120</td>
<td>7.7</td>
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<tr>
<td>0.135</td>
<td>6.9</td>
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<tr>
<td>0.156</td>
<td>6.0</td>
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<tr>
<td>0.178</td>
<td>5.3</td>
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<tr>
<td>0.200</td>
<td>4.8</td>
</tr>
<tr>
<td>0.215</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Table 6.1. Representative Open Areas of Various Continuous-Slot Screens Constructed with Different Wire Shapes.
For best well efficiency, the percentage of open area in the screen should be the same as, or greater than, the average porosity of the aquifer material. Typical porosities for sandstone and sand and gravel deposits are presented in Table 6.2. Continuous slot screens often equal or exceed the open area of the natural aquifer material except where unusually small openings must be used to control fine sand. Water flows more freely through a screen with a large intake area compared to one with limited open area. The entrance velocity through the larger intake area is low, and therefore the head loss for the screen itself is at a minimum. This, in turn, minimizes drawdown in the well at a given rate of pumping. The characteristics of the continuous V-shaped slot openings are vital to successful development and completion of a screened well. Any development method depends on having the smaller sizes of sand and silt pass through the screen openings, which must be nonclogging and closely spaced. Development is most effective when the screen openings are evenly spaced around the circumference of the screen, the open area is as large as possible, and the configuration of the slot openings allows the development energy to reach into the formation.

<table>
<thead>
<tr>
<th>Material</th>
<th>Porosity, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel, coarse</td>
<td>28*</td>
</tr>
<tr>
<td>Gravel, medium</td>
<td>32*</td>
</tr>
<tr>
<td>Gravel, fine</td>
<td>34*</td>
</tr>
<tr>
<td>Sand, coarse</td>
<td>39</td>
</tr>
<tr>
<td>Sand, medium</td>
<td>39</td>
</tr>
<tr>
<td>Sand, fine</td>
<td>43</td>
</tr>
<tr>
<td>Sandstone, fine grained</td>
<td>33</td>
</tr>
<tr>
<td>Sandstone, medium grained</td>
<td>37</td>
</tr>
</tbody>
</table>

*These values are for repacked samples, all others are undisturbed.

Table 6.2. Representative Values of Porosity

6.1.1. Screen Diameter

Continuous-slot well screens of welded construction are available in two series of diameters: telescope-size and pipe-size screens. Telescope-size screens are designed to be placed in wells by "telescoping" them through the well casing. The diameters of telescope-size screens allow them to be lowered freely through the corresponding size of standard pipe which serves as well casing. The screens in this series are designated by the nominal diameter of the pipe into which they will telescope. A 4-in telescope-size screen, for example, is actually 3-3/4 inches in outside diameter, which permits just enough clearance for it to pass through a Win standard pipe. Table 6.3 gives the screen dimensions and certain other data for selected telescope-size well screens. Lowering the well screen into place through the well casing is a common method of installation, because it eliminates any possibility of borehole caving. A plate is usually welded or threaded to the bottom of the screen. A bail hook can be mounted on the upper surface of the bottom plate to facilitate lowering the screen into the well. Threaded bottoms facilitate attachment of the hook.
Pipe-size screens have the same inside diameter as the corresponding sizes of standard pipe. Pipe-size screens are used when the well design specifies that the screen be attached directly to the well casing to maintain the same diameter for the full depth of the well.

### 6.2. Other Types of Well Screens

Several other types of well screens exist. Some of these are manufactured whereas others are hand perforated from casing or other materials. Under certain conditions, one or more of these screens may be adequate in some geologic formations, but may provide only marginal success under many other hydrogeologic conditions. Limited open area, poor slot configuration, and short-lived screen material contribute to their limited success. One very common well screen is slotted plastic pipe. Slotted plastic pipe is used to screen wells in some areas, particularly in clay-rich sediments (for example, clayey tills) where no aquifer zone can be identified. Slotted plastic screens are not affected by corrosive water, are easy to install, and are relatively inexpensive. In cold climates, some plastic materials must be handled with care to avoid breakage. The some limitations that apply to slotted metal pipe
also apply to plastic pipe. For example, slotted plastic screens have less than half the open area of continuous-slot plastic screens. In addition, plastic pipe materials are from one-sixth to one-tenth as strong as stainless steel well screens.

### 6.3. Well Points

Well points are made in a variety of types and sizes. The welded continuous-slot screen is made as a well point by attaching a forged-steel point to the lower end of a screen and a threaded pipe shank to the upper end (Figure 6.3). This type of construction is the most efficient hydraulically. The most common sizes are designed for direct attachment to either 1-1/4-in or 2-in pipe. Continuous-slot well points are constructed of either low carbon steel or stainless steel. The sizes of openings are designated by numbers that correspond to the actual width of openings in thousandths of an inch or the metric equivalent. Although these units can withstand hard driving, they should not be twisted while being driven or used in areas where boulders or large stones are expected unless special installation methods are used.

Another type of well point consists of a perforated brass or stainless steel jacket covering a perforated pipe, with an intervening layer of wire mesh. The perforations in the steel pipe core, less the obstruction of the mesh and outer jacket, constitute the effective intake area for this type of well point. The forged-steel-point bottom has a widened shoulder designed to
push gravel or stones aside and reduce the danger of ripping or puncturing the jacket as the well point is being driven into the ground. The relatively low open area of this type of well point may cause high rates of incrustation in hard waters and the bimetal construction often leads to excessive galvanic corrosion in waters with a low pH.

Still another type of well point design is a galvanized pipe with half-moon shaped perforations. A layer of stainless steel mesh is wrapped on a plastic pipe insert which is slipped inside the galvanized pipe. Although the intake area of the screen is not large, the wire mesh is reasonably well protected from rocks and stones during driving. The size of the screen openings is designated by the mesh number, which is the number of openings per linear inch. Common sizes are 40, 50, 60, 70, and 80 mesh.

6.4. Optimum Well Screen Open Area

The desirable percentage of open area in a well screen should at least equal the porosity of the water-bearing sand or filter pack. Assume the sand has 30 percent porosity and the well screen installed in the sand has 10 percent open area. The difference causes a constriction of flow as water enters the well. This means more drawdown for a given pumping rate, because additional head loss occurs as water passes through the screen openings. Thus, screened wells perform best when the intake area of the screen is as great as possible for a particular slot opening and strength requirement.

For wells completed in fine-sand formations, most well screens cannot provide a percentage of open area equivalent to the sediment porosity. The size of openings required to control the fine sand is often so small that even the best continuous-slot screen will fall somewhat short of matching the porosity. Porosities for well-sorted sands vary from about 20 to 40 percent. If a No. 10 (0.010 in) slot screen is needed, the most efficient screen construction (continuous-slot with narrowest wire) would provide a little more than 18 percent open area. If the slot is increased to No. 20 (0.020 in), the open area is 30 percent. However, many inefficient screens have less than 10 percent open area. Slotted pipe, for example, may have as little as 2 percent open area. Thus, the continuous-slot screen is the only type that can approximate the natural porosity of well-sorted aquifer material for the full range of screen slot size.

6.5. Sediment Size Analysis
Selection of slot size is a critical step in assigning maximum well performance. The slot size of the screen is based on a size analysis of the formation samples. By analyzing the component sizes of the grains in the sample, a grain-size distribution curve can be drawn. Several methods can be used to obtain information on the grain-size distribution. The most widely used method involves passing the materials through a stacked set of 8-in brass or stainless steel sieves which are shaken in a special vibration machine. During the sieving process, each sieve filters out a certain percentage of the entire sample; the finest material collects in the bottom pan. Plotting of these percentages (weights) of the whole sample provides an insight into the physical makeup of the sample (figure 6.3).

Other methods to determine the grain-size distribution include sedimentation analysis using velocity settling tubes for sediments smaller than 0.003 in and automatic particle size analyzers with computer printouts of grain size distribution data by x-y plotters. Because sieving is the most common method used to determine the grain-size distribution, much of the discussion which follows will focus on the correct procedures to use when sieving.

6.51. Sediment Size

In describing the fineness or coarseness of a granular material, the terms fine sand, coarse sand, fine gravel, and other similar terms are used. Unfortunately, these terms do not apply to specific particle sizes, which results in various scientific and engineering specialties using different terms for sediments of the same size. Therefore, several different grain-size classifications have been developed to define each descriptive term. Each of these systems has been adopted in the special field where it seems to fit the best.

The Wentworth scale, developed in 1922, is still the basic particle size classification used in the groundwater field. The United States Geological Survey (USGS) uses this classification but has taken one size range, 0.16 to 2.5 in, and subdivided it into groups. The Wentworth scale and USGS amendments are shown in Table 6.4.
The curve in Figure 6.4 shows that the sample tested consists of medium and coarse sand, according to the USGS classification. Applying the same system to the fo~ curves in Figures 6.5 to 6.8 gives the following descriptions:

- Class A curve—fine sand
- Class B curve—fine and very coarse sand
- Class C curve—coarse and very coarse sand
- Class D curve—coarse sand and very fine gravel

6.5.2. Slope and Shape of Curve
The slope of the major portion of a grain-size distribution curve can be described in several ways. One term that is used extensively is the uniformity coefficient, which was developed by Hazen at the same time he adopted the idea of effective size. Uniformity coefficient is defined as the 40 percent retained size of the sediment divided by the 90 percent retained size. The lower its value, the more uniform is the grading of the sample between these limits. Larger values represent less uniform grading. The uniformity coefficient is limited in practical application to materials that are rather uniformly graded. It is meaningful only when its value is less than 5. It is well suited for describing the desired uniformity of filter-pack materials. The uniformity coefficient for the sample in Figure 6.3 is 2.9 (0.026 in divided by 0.009 in). For the Class B curve, the uniformity coefficient is 2; for the Class C curve, its value is 3.

The grain-size distribution curves for most granular materials deposited by running water and wave action are referred to as S-shaped curves, although this term is properly applied only to the percent passing curves. The S-shape of the curve becomes distorted when gravel constitutes 15 percent or more of a mixture of sand and gravel. The curve in Figure 8.5 and the Class A and Class C curves are typical S-shaped distributions. The Class D curve has a "tail" of coarse material. Size distributions that result in S-shaped curves usually represent samples having higher porosities than are found in samples with a "tail"-type configuration.

There is yet no accurate way to calculate hydraulic conductivity directly from the grain-size distribution curve. Many tests and research studies have been performed to find a simple relationship between the grading of a sediment and its hydraulic conductivity, but no dependable correlation that may be applied generally has yet been discovered. Nevertheless, with practical experience, it is possible to estimate the relative yields of different sand and sand and gravel mixtures by careful consideration of the three factors described in this section.

CHAPTER 7.

WATER WELL DESIGN

7.1. WELL SCREEN LENGTH

The optimum length of well screen is based on the thickness of the aquifer, available drawdown, and nature of the stratification of the aquifer. In virtually every aquifer, certain zones (horizons) will transmit more water than others. Thus, the intake part of the well must be placed in those zones having the highest hydraulic conductivity. Determination of the most productive layers can be made by one or more of the following techniques:

1. Interpretation of the drillers log and comments on drilling characteristics such as fluid loss, penetration rate, and pulldown and chatter.

2. Visual inspection and comparison can be made of samples representing each sediment layer. The relative transmissivity of each layer is estimated from the observed coarseness, lack of silt and clay, and thickness of the layer.
3. Sieve analyses can be made from samples taken from the various layers in the aquifer. Comparison of grain-size curves can indicate the relative hydraulic conductivity of each sample. The curves presented in Figure 7.1 indicate the relationship between the grain-size distribution of aquifer materials and the resulting hydraulic conductivity.

4. Laboratory hydraulic conductivity tests can be performed on samples that represent individual layers of the water-bearing formation. In this test, water is caused to flow through a sample the material. Measurements of the area through which flow occurs, the rate of flow, and the corresponding head loss provide data for calculating the hydraulic conductivity. Aquifer transmissivity can then be determined by adding the individual transmissivity values for all layers of the aquifer (transmissivity equals the hydraulic conductivity times the thickness for each layer).

5. Borehole geophysical logging techniques can help locate zones having the highest hydraulic conductivity. Velocity meter surveys also are extremely useful. Each technique listed above provides useful information on the zones that should be exploited. As many of these techniques should be used as possible.
Recommended screen lengths for four typical hydrogeological situations are given below.

1. Homogeneous Unconfined Aquifer. Theoretical considerations and experience have shown that screening of the bottom one-third to one-half of an aquifer less than 150 ft thick provides the optimum design for homogeneous unconfined aquifers. In some cases, however, particularly in thick, deep aquifers, as much as 80 percent of the aquifer may be screened to obtain higher specific capacity and greater efficiency, even though the total yield is less.

A well in an unconfined aquifer is usually pumped so that, at maximum capacity, the pumping water level is maintained slightly above the top of the pump intake or screen. The well screen is positioned in the lower portion of the aquifer because the upper part is dewatered during pumping.

For wells in unconfined aquifers, selection of screen length is a compromise between two factors. On the one hand, higher specific capacity is obtained by using the longest screen possible. This reduces convergence of flow and entrance velocity, thereby increasing specific capacity. On the other hand, more available drawdown results from using the shortest screen possible. These two conflicting aims are satisfied, in part, by using an efficient well screen that minimizes the loss in specific capacity as drawdown increases.

2. Nonhomogeneous Unconfined Aquifer. The basic principles of well design for homogeneous unconfined aquifers also apply to this type of aquifer. The only variation is that the screen or screen sections are positioned in the most permeable layers of the lower portions of the aquifer so that maximum drawdown is available. If possible, the total screen length should be approximately one-third of the aquifer thickness.

3. Homogeneous Confined Aquifer. In this type of aquifer, 80 to 90 percent of the thickness of the water-bearing sediment should be screened, assuming that the pumping water level is not expected to be below the top of the aquifer. Maximum available drawdown for wells in confined conditions should be the distance from the potentiometric surface to the top of the aquifer. If the available drawdown is limited, however, it may be necessary to draw the well down below the bottom of the upper confining layer. When this occurs, the aquifer will respond like an unconfined aquifer during pumping.

Screen lengths chosen according to these rules make it possible to obtain about 90 to 95 percent of the specific capacity that could be obtained by screening the entire aquifer. Best results are obtained by centering the screen section in the aquifer. In the past, screens were often interspaced with blank casing placed in the less permeable zones of the formation. Today, however, higher water demands and lower screen costs have resulted in completely screening most deep wells.

4. Nonhomogeneous Confined Aquifer. In this type of aquifer, 80 to 90 percent of the most permeable layers should be screened.

### 7.2. DESIGN OF DOMESTIC WELLS

Many of the design requirements for high-capacity industrial municipal, and irrigation wells also apply to domestic, farm, and stock wells. The selection of well screen openings, entrance
velocity requirements, and recommended screen and pipe material are as important for these wells as for high-capacity wells.

Thousands of wells are drilled every year for homes and farms where the total water requirements may be 5 to 30 gpm. For these requirements, long screens in relatively thick aquifers would be uneconomical. The farmer and the homeowner, however, need a dependable water supply that can be obtained with reasonable drawdown. In these cases, a compromise is necessary between well cost and well efficiency.

The drilling contractor must insure that enough potential drawdown is available to meet present and future yield requirements.

It is difficult to specify exact rules for choosing the screen length for low-capacity wells. For economic reasons, many domestic and farm wells must be constructed in less prolific aquifers and at depths that do not provide maximum hydraulic efficiency. In general, domestic wells should be constructed with screens 4 to 5 ft long; for farm wells, the screens should be 10 to 15 ft long, depending on the hydraulic characteristics of the aquifer and the yield requirements. These recommendations apply to continuous-slot screens only. For other types of slot configurations, much longer screens may be required. The examples cited below demonstrate how short screens are used in typical situations.

For the situation shown in Figure 7.2A, only 4 or 5 ft of the aquifer needs to be screened for a domestic well because of the relatively high static water level and high hydraulic conductivity of coarse sand. For a farm well the screen length should be increased to 10 ft (3 m) because the required yield is usually higher. The reduction in available drawdown is not a problem because the transmissivity of the aquifer is adequate.

For the situation in Figure 7.2B, most of the medium sand should be screened. If a screen of this length does not provide sufficient open area for the desired yield, the screen may have to be extended a short distance into the finer sand above, although the contribution to the yield from the added screen footage may not be significant. In this case, sufficient drawdown is available if the screen is lengthened.

The screen for the well in Figure 7.2C should be set at the bottom of the coarse sand layer if adequate drawdown is available (as shown here). The length of the screen should be about one-third the thickness of the coarse sand. Ordinarily, it would not be beneficial to extend the screen deeper into the fine sand, because good yields from highly stratified silt/sand layers are considerably more difficult to obtain.

In Figure MID, the hydrogeologic conditions are not as favorable. Although the static water level is high enough to provide adequate drawdown for a farm well, the thickness of the sand layers is limited. In fact, the two lower sand layers should be partially screened to provide enough open area to the formation. In this case, two 3 ft sections of screen are placed in the lower portion of the deep sand formations and connected by blank pipe. The top of each screen should be kept 3 ft below the top of the aquifer to allow for anticipated sloughing of overlying clay during development. This type of installation is relatively common in glaciated terrains, but requires careful logging of the well by the drilling contractor.
Although screens longer than 10 to 15 ft may not be necessary in domestic or fawn wells to meet present yield requirements, water demands almost invariably increase with time. Contractors should anticipate these greater demands by installing screens of sufficient length to provide for increases in yield, because screen cost is usually a minor part of the total well cost. The yield of a well may be increased almost in proportion to an increase in screen length, provided the well taps water-bearing formation of reasonable thickness. For example, doubling the screen length can, in most cases, almost double the well yield. Doubling the diameter, however, can be expected to increase yield only about 10 percent, except when the yield is restricted only by pump size and a larger diameter pump would increase yields substantially.

Small wells should also be constructed with screens and casing of sufficient diameter so that effective development methods and tools can be used. Many wells are completed with 2-in drive points driven out of 4-in casing. Although these wells are satisfactory from a design standpoint, they are difficult to develop properly.
7.3. DESIGN FOR SANITARY PROTECTION

The design of a water well supplying potable water should include those features that provide continuous sanitary protection. Contaminated water from surface drainage or low-quality water encountered in the well can move downward through the annulus between the casing and borehole wall. Thus, the annulus around the casing must be sealed. Generally, any sealing around the well involves placing a cement grout in the annulus; bentonite is sometimes used in place of cement.

7.4. SPECIAL WELL DESIGNS

Various design methods have developed in certain areas because of particular Hydrogeologic conditions, the type of drilling equipment used, the availability of filter pack material, and the economic aspects of the wells. These methods and procedures were developed because more water was needed than could be obtained with standard design criteria and because favorable cost/benefit ratios were realized. Although developed locally, these methods can be used successfully in areas where similar hydrogeologic conditions exist. Several examples of alternative well designs are described below.

Case 1

Hydrogeologic conditions: High-quality water found in sinuous, thin alluvial and glaciofluvial deposits in river valleys. Small volumes of water also found in underlying igneous and metamorphic rocks.

Problem: Underlying bedrock aquifers do not offer sufficient volumes of water. Alluvial and glaciofluvial aquifers are small in areal extent and are relatively thin. These aquifers are sustained, however, by high rates of induced filtration from nearby streams or rivers.

Solution: To pump large volumes of water at low incrustation rates, the screen slot size must be as large as possible because the screen length is limited. This is accomplished by placing two filter packs around a large-diameter, but necessarily short, screen segment, thereby increasing the effective diameter of the screen. The purpose is to reduce the amount of drawdown required to drive water into the screen by greatly increasing the porosity and hydraulic conductivity of the material adjacent to the screen. The outer peck is selected to control movement of the aquifer materials, whereas the inner pack retains the outer pack material. The inner pack is much larger in particle-size distribution than is the outer peck, so the screen slot size is also much larger. In this design, the intake area of the short screen is maximized by increasing the diameter (it cannot be lengthened), and the slot size is considerably larger than could be achieved with a single pack. Thus, high yields are obtainable at low incrustation rates from short screen sections when they are located in highly permeable sediments near sources of recharge.

Case 2

Hydrogeologic conditions: High quality water exists in near-surface thin sand layers that are underlain by thick clay layers. The underlying bedrock contains only low quality water that is not suitable for potable supplies.
Problem: Yields from conventional wells are insufficient for even domestic use because the aquifers are thin. Water tables fall enough during fall and winter to cause wells to go dry.

Solution: A 24 to 48-in borehole is drilled through the overlying sand layer into the clay, usually by bucket or earth auger. The borehole is kept open below the water table by keeping it filled with water and by adding drilling fluid additives to reduce fluid losses. A 1- to 2-ft length of continuous-slot screen is installed in a string of casing so that the screen is placed at the bottom of the aquifer (Figure 7.3). The pump intake is placed in casing (sump) that extends beneath the screen. During periods of nonpumping, water cascades into the sump, which acts as a reservoir. The bottom of the casing stung is usually sealed with cement or a steel plate. The screen is filter packed, but the annulus above and below the screen may be filled with gravel, sand, or clay. Yields from this type of installation will vary according to the fineness of the sand layer and the depth of the water table, but sustained yields are usually much greater than can be expected from a typical well installation and are generally adequate for most domestic water demands.

Case 3

Hydrogeologic conditions: Extremely small volumes of water are found throughout thick, dirty, fine-grained sand/silts/one sequences that are buried at depth and may be under confined pressures.

![Figure 7.3](image)

**Figure 7.3.** To intercept the limited volume of water in a thin, surficial, sand aquifer a short segment of large-diameter continuous-slot screen is installed at the base of the formation. Water entering the well collects in a sump beneath the screen. The pump is ordinarily mounted in the sump to permit removal of the maximum volume. (Larson, 1979)

Problem: It is not economical to set large-diameter screens because of the potentially small yields and the difficulty in identifying the most productive zones.
Solution: To obtain a reasonable yield, a string of 2-in continuous-slot screen, commonly 40 to 100 ft long, is installed through the full thickness of the formation. The screen may be filter packed or the annulus filled with a formation stabilizer, depending on how well the aquifer materials are cemented together. Anticipated yields from this type of screen installation are usually 40 to 60 8pm.

Case 4

Hydrogeologic conditions: In coastal areas with high annual rainfall, a thin 2- to 3 ft veneer of fresh water sometimes overlies saline water. The fresh water is of high quality, but can be easily contaminated with salt water unless pumping rates are kept low.

Problem: Ordinary well designs cause salt water to cone upward during pumping, leading to contamination of the overlying fresh water.

Solution: To obtain reasonable volumes of high quality fresh water, it is necessary to eliminate the upconing effect. This is done by installing several widely spaced well points that are then manifolded together and pumped by suction lift. The points are pumped lightly to minimize pressure reductions in the vicinity of the points. The water is stored in a 500-gal tank. A separate pump is used to move the water from the tank to the house system. With conservative use, a single tank may provide enough water for several days for a family.

CHAPTER 8.

INSTALLATION AND REMOVAL OF WELL SCREENS

Well screens are required in all unconsolidated and most semiconsolidated formations, and occasionally in consolidated rock. Many different screen installation methods are used, although certain procedures may be more practical or more economical in certain areas or when particular drilling rigs are used. The exact procedures to be followed when installing a well screen depend on the nature of the aquifer materials, the method used to drill the well, the dimensions of the borehole, the hydraulic conditions in the aquifer, and the casing and screen materials. Well completion steps that are done during installation or immediately thereafter include installing the filter pack materials, grouting the casing, and developing the well. The most common and successful screen installation methods are described below.

8 1. PULL-BACK METHOD

Before the recent increase in the number of direct rotary drilling rigs, the pull-back procedure was used in most wells. It is a safe method of installation that reduces problems resulting from heaving sediment, sloughing of the borehole walls because of swelling clays or insufficient hydrostatic pressures, and setting the screen at the wrong depth. The pull-back method also permits the screen to be removed and replaced if necessary, without disturbing the sanitary grout seal outside the well casing. The cost of pulling, cleaning, or replacing the screen is usually small in comparison with drilling a new well. The pull-back procedure is particularly suited for wells drilled with a cable tool rig and with air rotary rigs equipped with casing drivers, although some direct rotary drillers use it as their standard method of installation for shallow wells.
The pull-back method involves insuring the casing to the full depth of the well, lowering (telescoping) the well screen inside the casing, and then pulling back or lifting the casing far enough to expose the screen to the water-bearing materials (figure l0.1 ). The casing must be strong enough to be set the full depth of the well and then be pulled back the length of the screen.

Telescope-size screens are designed for use in the pull-back method. As the term "telescope" implies, the screen is constructed so that it will telescope through standard pipe of the corresponding size, allowing installation of the largest diameter screen possible for a given casing diameter. Occasionally, pipe-size screens that are one or more diameters less than the casing may be telescoped through larger diameter casing

8.1.1. Packers

A special fitting is required to provide a sand-tight seal between the top of the telescoped screen assembly and the casing. Two types of packers were commonly used: neoprene rubber (often called K packers) and lead. Lead is no longer acceptable. The packer is attached directly to either the top of the well screen or the top of a riser pipe.

A rubber packer is constructed of flexible neoprene rubber attached to a steel coupling and fits tightly in the casing, sealing the casing to the screen. The use of this type of packer has grown rapidly because no expansion of the packer is required. Frequently two or more packers are used in series to eliminate problems caused by small deviations in the dimensions of the casing or packer resulting from improper handling. Furthermore, multiple rubber packers are recommended for screens set at depths exceeding 300 ft because the rough inner surface of the casing, often caused by weld slag or beads in welded casing, can damage the rubber lips of the packer. Lubricating the lips of the rubber packer with petroleum jelly will reduce damage when the screen is lowered into the casing.
The packer is ordinarily attached to a riser pipe and expanded in the casing. The top of the packer is fitted with a left-hand thread so the drill pipe can be disengaged from the packer.

Inflatable packers generally have larger expansion ratios than do casing hangers. The packer is inflated by injecting gas, water, or a solidifying liquid. Thus, the packer can be used for a short time and then retrieved or installed permanently. Some fixed-end packers can be inflated to two times the uninflated diameter, but are generally designed for lower pressure applications than are sliding-end packers. Sliding-end packers are used where the differential pressures range from 200 to 2,000 psi or more. Inflatable packers are useful for effecting casing repairs, pumping tests of isolated zones in the borehole, hydrofracturing, and injecting water and gases.

Occasionally, a screen much smaller in diameter than the casing is used. For example, when a high yield is anticipated, a relatively large diameter casing may be needed to accommodate the pump bowls. A large diameter screen may not be needed or practical, however, because the open area of a smaller diameter screen is sufficient to accommodate the expected yield at properly designed entrance and uphole velocities. A special cone adaptor is then used to connect the smaller diameter screen to the larger packer needed for the casing. The packer and cone adaptor are attached to the screen before installation.

8.1.2. Setting the Screen in Wells Drilled by the Cable Tool Method

It is important to control sediment movement into the bottom of the casing because the screen should be set as close as possible to the designed depth. This is particularly important
if the screen has been designed with several slot sizes corresponding to individual sediment layers, or if blank sections have been placed between screen sections. If there is difficulty in keeping sediment from heaving inside the casing, the casing should be filled with water. Fluid losses may be controlled by using prepared drilling fluids. To keep confining pressures in the aquifer under control, the drilling fluid may be weighted with special high-density materials or salt. Sudden vertical movement of tools in the casing also increases the likelihood of heaving problems. Therefore, bailers should be operated slowly to reduce pressure differences at the bottom of the borehole.

After the casing has been driven to the proper depth, any sediment that has entered or settled within the casing should be removed carefully. After all sediment has been removed from the casing, the driller must be sure the casing can be withdrawn. If it cannot be withdrawn, the drive shoe is cut off with an inside casing cutter to reduce resistance, and the casing is pulled back a few inches. The screen is then lowered to the bottom of the welt. Several devices can be used to lower the screen: bail and hook, eccentric clevis (offset latch), eyelet screws mounted in packers, casing lugs (bayonet type), and wash-down bottoms.

If the screen is made in two or more sections, the bottom section is lifted by a rope clamp or hitch and suspended inside the casing by a pair of casing clamps or elevators. The next section is then threaded or welded to the top of the first section.

If the depth to water is less than 50 ft. short, small diameter screens may be installed by dropping them inside the casing. If rubber packers are used, screens 4 to 6 inches in diameter generally will not drop and must be pushed into place, whereas screens 8 in and larger will drop because of their weight. Careful measurements must be kept so the driller will know that the screen is set at the correct depth in the aquifer.

The drill string or a weight attached to the sand line should be placed on the bottom of the screen while the casing is being pulled back. This provides enough weight to keep the screen on the bottom, and the tension in the sand line serves to verify the exact position of the screen during the procedure. If weight is not applied to the screen, any heaving of the formation will force the screen upward at about the same rate that the casing is pulled back.

The casing can be pulled back by one of several methods. Under ideal conditions where the earth materials have not collapsed tightly around the casing, it can be pulled with the casing line on the cable tool drilling machine. Greater lifting force can be obtained by using a block and tackle attached to the casing line. If the casing cannot be withdrawn by the casing line, it may be pulled by jarring with the drilling tools with fishing jars attached, or a bumping block or drive clamps. Mechanical or hydraulic jacks may also be required to provide the necessary lifting force. If so, a pulling ring or spider with wedges or slips is used to grip the casing. For long casing strings, a vibration hammer is effective in overcoming the skin friction between the casing and formation. Although the cost of this procedure may be high when compared with other methods, it is sometimes the only method powerful enough to withdraw casing.

As the casing is being pulled back to expose the screen in the water-bearing formation, depth measurements to the screen are taken. If no riser is attached to the screen, the casing should be pulled back so that the packer is about 12 in above the bottom of the casing. The screen can be fully exposed beneath the casing if a riser pipe is attached to the top of the screen.
8.1.3. Setting the Screen in Wells Drilled by the Rotary Method

When screens are installed in rotary-drilled wells, the pull-back method should be selected if caving conditions exist or lost circulation is a problem. Drill pipe should be withdrawn slowly from the hole after the maximum depth has been reached to eliminate heaving caused by suction. The presence of the drilling fluid column will usually control caving problems, except in relatively shallow, unconsolidated glacial or alluvial sediments. Natural compaction of these sediments is not great, and in confined aquifers the material is close to a condition where any suction or other disturbances in the borehole will cause the sediment to "run" toward the low-pressure (suction) zone.

Setting the casing to the bottom of the hole and then pulling it back may appear to be extra work, but this operation prevents serious problems arising from premature caving which can occur when the drilling fluid viscosity is reduced prior to development. The protection given by the casing is particularly important if a delay is anticipated between drilling and screen installation. During this period, a momentary loss of drilling fluid may cause partial collapse of the borehole.

After the casing is placed in the open borehole, any cuttings that settle inside it are carefully cleaned out. The screen is then lowered to the bottom through the casing and the casing is pulled back to expose the screen. After the casing is pulled back, it must be held in place until the fannation has caved around it during development or until the annulus has been backfilled or grouted.

For wells drilled with air rotary machines equipped with casing drivers, two setting procedures can be followed, depending on the stratigraphy. In heaving formations, the casing is usually sunk to the top of a clay layer under the aquifer, the screen set within the casing, and the casing pulled back. If no clay exists and heaving is a problem, it may be necessary to change from air-based to water-based drilling fluids to control fluid pressures in the formation so the screen can be set. Occasionally, stiff foam may be enough to control the formation. In thin aquifers, it is also extremely important that the switchover be accomplished before the borehole is over-excavated. Excessive excavation may cause collapse of weaker overlying sediments, which may destroy the hydraulic characteristics of a thin aquifer in the vicinity of the well. Once heaving has been controlled, the casing can be cleaned by circulating water-based drilling fluids. The screen is then installed and the casing pulled back.

8.2. OPEN-HOLE METHODS FOR SCREEN INSTALLATION

8.2.1. Double-String Installation

Use of the pull-back method in rotary drilled wells has declined in favor of open hole methods. A common procedure for installing screens in high-capacity industrial and municipal wells is described below. Because this is only an example, not all alternative methods for individual steps are included; however, other procedures are presented later in this chapter.
A typical procedure for installing screens in high-capacity wells includes the following steps:

1. Drill a small-diameter test hole at the chosen site, keeping a detailed drilling log and collecting samples at specific intervals. Samples are taken at each formation change and every 5 to 10 ft. depending on the formation thickness and well depth.

2. Conduct geophysical logs (typically SP, resistivity, natural gamma ray, and hole caliper) in the test hole and determine which aquifer or aquifers are to be screened. Occasionally, side-wall cores are taken to verify the type of formation and its hydraulic characteristics.

3. If more information about the aquifer is needed, such as chemical quality or productivity, a 2- to 5-in screen is installed in the desired zone and test pumped.

4. After the production zone is chosen from an analysis of the cuttings, driller's logs, geophysical logs, and pumping test data, samples are analyzed and the correct screen-slot openings are determined.

5. If a test well has been drilled, the screen and casing are pulled and the test hole is then used as a pilot hole for the production well. In uniform geologic conditions, the test hole is often left as an observation well and the production well is drilled a suitable distance away. The test hole can also provide make-up water for use in drilling the production well.

6. An open hole is then drilled down to the top of the aquifer to receive the casing. The hole diameter should be large enough to allow space in the annulus between the casing and the hole for a minimum grout thickness of 2 in.

7. The casing is set in the hole. Generally, a drillable grout shoe (plug) constructed of cast aluminum or cement is installed on the bottom of the casing. The shoe allows the grout to be pumped through the bottom of the casing and should be used on the casing to insure proper centering.

8. The casing is then grouted. At least 24 hours should be allowed for the grout to set.

9. Any extra grout in the casing and the drillable shoe is next drilled out, but the aquifer is not penetrated. At this point, all drilling fluid used to drill the grout should be replaced with clean drilling fluid or water if practical. This is an important step; if the grout-contaminated fluid is used to drill the aquifer, it may seal some of the formation and be difficult, if not impossible, to remove from the formation. It may also have an adverse effect on the physical characteristics of the drilling fluid.

10. If the well is to be naturally developed, the aquifer is drilled with a bit that is slightly smaller than the inside diameter of the casing. If the well is to be filter packed and the diameter of the completed borehole is too small to accommodate a proper thickness of filter pack between the screen and formation, the aquifer may be underreamed to obtain a 3 to 8-in annulus.

11. A suitable length of riser pipe should be used on top of the screen. If there is to be blank pipe between the top of the screen and the bottom of the casing and the well is filter packed,
a 5-ft length of pressure-relief screen should be included in the riser pipe stung and set at the bottom of die casing (pressure-relief screens are discussed in the filter-pack section).

12. A screen is then telescoped through the casing into the open hole by an offcentered latch hook, bail hook, or left-hand-threaded fittings attached to the plate bottom of the screen or to the top of the riser pipe. The last method is the surest way to position the screen; but in deep holes where the drill pipe exerts high pressure on the threads, the drill string should be held back or a slip section should be used to reduce the weight on the threads while disengaging the drill pipe from the screen. Sometimes a fin (piece of flat metal) is welded to the side of the screen bottom plate to prevent the screen from turning when unthreading the drill pipe. Metal bars or other attachments welded underneath the bottom plate will also prevent the screen from turning. If the well is to be filter packed, it is recommended that one centralizer be attached near the bottom of the screen and another near the top. For screens of less than 200 ft. centralizers should be spaced every 20 ft; for economic reasons, centralizers are often spaced at 20 ft intervals on screens over 200 ft.

13. If it is anticipated that fill or other borehole material may prevent the screen from reaching the desired depth, a self-closing bottom fitting with internal left-hand threads can be mounted in the screen bottom plate to wash the screen into place. A wash pipe is attached to this fitting and can be used to set the screen. A washbowl bottom provided with a slip-socket wash fitting is sometimes mounted on the bottom of the screen but is not used to set the screen. Instead, these fittings are useful in displacing drilling fluid from the borehole, thereby aiding development. The displacing fluid, often clear water, is directed through the wash-down bottom to remove the drilling fluid from the hole. If an open-bottom screen is used, cement grout can be used to plug the bottom.

14. After the screen is set, the well may be naturally developed or filter packed. If the well is to be naturally developed, the formation is induced to cave around the screen by reducing the hydrostatic pressure in the borehole, by either thinning the drilling fluid or lowering the level of the drilling fluid in the borehole. The setting tool is then removed and the driller begins development.

If the well is to be filter packed, the setting tool is left in place while filter pack is introduced into the well. A plug can be used to temporarily close the top of the screen during filter packing. After the filter pack is in place, the setting tool or plug is removed and the well is developed. Normally no packer has to be installed if the riser pipe is lapped 50 ft or more into the casing and a pressure relief screen is installed.

8.2.2. Single-String Installation

In most small-diameter, rotary-drilled wells completed in unconsolidated sediments, the screens are attached directly to the bottom of the casing. Screens that are smaller in diameter than the casing can be welded or threaded directly to the casing by mounting a cone adaptor or flared weld ring to the top of the screen. Screens that are the same size as the casing can be welded or threaded directly to the bottom of the casing.

The casing and screen are then set in the hole and the drilling fluid is thinned. If the drilling fluid is not thinned, the fluid may not enter the screen as it is lowered into the borehole. High differential pressures can then be created, which may be sufficient to collapse the screen.
Under these conditions, it is prudent to fill the screen with water when it is placed in the borehole. For naturally developed wells, the formation is induced to cave in around the screen and casing immediately after the screen is set. When wells are filter packed, the pack material is placed before the formation is induced to cave.

To prevent clay-rich material above the aquifer from sloughing next to the screen during natural development, a formation stabilizer is often instated. The formation stabilizer holds the clay in place until the materials cave against the stabilizer. The size gradation of a stabilizer should be similar to the formation material or a little coarser. In most cases, however, a formation stabilizer is not needed if the borehole is only slightly larger than the screen and the top of the screen is placed 3 ft or more below any clay zone.

8.3. FILTER PACKED WELLS

Many wells drilled by cable tool or rotary methods are designed for a filter pack, thereby altering the screen installation process. Filter-packed wells differ from naturally developed wells in that an envelope of specially graded sand or gravel is placed around the well screen to a predetermined thickness. This takes the place of the graded zone of permeable material that is produced by the natural development process. Both types of wells, when properly constructed, are efficient and stable. The geologic conditions, availability of suitable filter pack materials, drilling method, and type of screen determine whether a filter pack should be used.

The thickness of the filter pack is a primary factor in the effectiveness of the development procedures taking place at the interface of the pack and formation. The minimum practical thickness for the pack is 3 m. Filter packs thicker than 8 in are not recommended, because the effectiveness of the development procedures may be impaired.

8.3.1. Selection and Placement of Filter Pack

It is important to select a filter pack that will not segregate, because sand pumping can result if fine and coarse particles become separated during placement. It can be demonstrated that a round particle of a given size and density falls through water four times faster than a round particle half as large and with the same density. If filter pack material that is uniformly graded from 1/16 in to 1/8 in is allowed to fall through water as separate grains, the 1/8-in grains will reach the bottom of the well in one-fourth the time required for the 1/16 in grains. Thus, well-sorted filter pack material is less apt to segregate than is pack material with a wide range of particle sizes. Sand and gravel mixtures with uniformity coefficients greater than 2.5 are difficult to place without undesirable separation of coarse and fine fractions. All filter pack materials should be treated with a bactericide, usually chlorine, before placement to insure that the well does not become contaminated. All water used in the filter pack operation and any tools or pieces of installation equipment should also be treated with a 50 mg/l free-chlorine solution before use. Whenever possible, the drilling fluid should be thinned before placing the pack material.

Use of a tremie pipe to install the filter pack will minimize the tendency for particle separation and bridging, this is the preferred method for filter pack placement, especially for packs with high uniformity coefficients. A string of 2-in or larger pipe is lowered into the annular space to be filter packed. The filter pack material is fed into a hopper at the well
head. A liberal supply of water should be introduced with the filter pack to help prevent
bridging of the material in the pipe. A typical ratio of water to pack material is 5 to 10 gal for
each 1 ft³ of pack material when a 2-in tremie pipe is used. The tremie system is practical for
placing the filter pack in shallow to moderately deep wells (to 2,000 ft). In some cases, filter
pack material may be pumped through the tremie pipe along with the water stream instead of
being driven by gravity.

During installation of the pack the tremie pipe is raised periodically as the filter material
builds up around the well screen. The tremie pipe or a weighted line inserted through the
tremie can be used to feel the top of the filter pack and to measure the depth to the pack as
the work progresses.

Direct circulation of clean water can also be used to reduce bridging problems.

**8.3.2. Filter Pack Procedures for Wells**

**8.3.2.1. Drilled by the Cable Tool Method**

Several different casing arrangements may be used for filter pecking wells drilled by the
cable tool method In one type of installation, the screen is connected to an inner casing,
centered in a larger borehole, and surrounded by filter pack material The inner-casing will
become part of the completed well structure and may accommodate the pump. In deep well
installations, the inner casing may not extend all the way to the ground surface. A
large-diameter outer casing is first set to the full depth of the well. An inner casing and well
screen are then centered in the outer casing, using centering guides. The selected filter
material is placed in the annular space around the screen and extended high enough above the
screen to accommodate settlement of the filter pack after the outer casing has been pulled
back. The filter pack material should extend above the top of the screen about one-fourth the
screen length.

The pack is usually placed in stages as the outer casing is pulled back. Dive feet of filter pack
material should be maintained above the screen as the casing is withdrawn. During
withdrawal, depth to the top of the filter pack must be monitored carefully by a sounding line
or tremie pipe to insure that the level never drops below the outer casing. The driller must be
careful, however, not to overfill the annulus during withdrawal because a sand lock may
develop between the outer casing and screen.

After the filter pack is installed, development work is continued to remove fine sediment
from the filter pack and to clean the contact surface between the filter pack and the
formation. As development proceeds, some settlement of the filter pack will occur and more
filter pack must be added to keep the level above the screen. After development, the annular
space above the filter pack should be sealed by bentonite pellets or cement grout. The outer
(surface) casing may be removed or left in place.

**8.3.2.2. Filter Pack Procedure for Wells Drilled by the Rotary Method**

In most rotary-drilled wells, the screen and casing are placed in the borehole as a unit. The
screen may be the same diameter as the casing or slightly smaller. Centralizers are generally
attached every 20 ft on the screen body and every 40 ft on the casing. The casing should be
held in tension while the drilling fluid viscosity is reduced as much as possible without allowing collapse of the well bore. Thinning the drilling fluid reduces development time, minimizes flotation effects, and increases settlement rate for pack materials. Filter pack is placed by tremie pipe or other means into the annulus around the screen and usually extends some distance above the top of the screen. Filter pack material should be added as required during development. After development and backfilling of the borehole, the tension on the casing and screen is released.

8.3.3. General Guidelines for Installing Filter Packs

For filter pack installations, the pack should extend at least 25 percent of the screen length above the top of the screen. For example, a minimum of 50 ft of filter pack should be installed at the top of a 200 ft screen to provide an adequate reservoir. The top of the riser pipe should be well above the top of the filter pack or outer casing bottom, especially if no packer is used at the top of the riser pipe.

8.4. INSTALLATION OF PLASTIC SCREENS

More plastic materials are now being used for well screens, especially in smaller diameter wells. Plastic materials have predictable physical limitations, but when selected and used properly they provide wells with adequate structure strength, good hydraulic characteristics, and long life. For depth settings exceeding 300 ft, the screen manufacturer should be contacted for recommendations concerning wall thicknesses.

Plastic screens can be set in many of the same ways as steel materials, but plastic does not have the inherent strength of steel and special care must be taken during installation and well completion. In addition, unlike steel, plastic casing may be buoyant when placed in the well depending on the depth to the water table and the density of the drilling fluid. Thus, setting procedures may have to be modified. It was originally felt that plastic screens would be used only by rotary drillers and be attached directly to plastic casing. Today, however, plastic screens are being installed with steel casing, and steel screens with plastic casing, by both the telescope and the direct-attached methods in rotary drilled holes.

In the past, several plastic materials were used in a variety of different wall thicknesses and schedule numbers. Currently, PVC material constructed to Schedule 40, 80, or SDR-21 specifications are becoming the most common plastic materials used in water wells. A wide variety of standard end fittings are available for all types of plastic pipe. Because plastic pipe has standard outside dimensions, end fittings built by different manufacturers are generally interchangeable. There may be extremely small differences in dimensions, however, so for best results and where maximum performance is required, it is advisable to use pipe fittings and pipe from the same manufacturer. PVC fittings are useful in attaching PVC to steel, or vice versa. Fittings such as male adaptors, female adaptors, reducers, and slip couplings are available to fit any threaded fitting on the market.

8.4.1. Telescope Installations

Plastic screens can be telescoped through plastic or steel casing, but the varying inside diameter of plastic casing (depending on schedule or SDR number) may cause some problems in obtaining the best fit between packer and casing. Rubber packers are typically
used, but because the outside diameter of the rubber sealing ring is constant the fit may be
either tight or loose, depending upon the wall thickness of the plastic casing. For example, in
Din pipe, there is a Q046-in difference in inside diameters between Schedule 40 and SDR-21.
Although the difference in diameter is small, it could cause serious sand pumping in a well
completed in fine sand.

Even though plastic-based rubber packers are available, the drilling contractor should make
sure that the packer is suitable for use with the particular plastic pipe being installed.

8.4.2. Setting Screens in Open Boreholes (Direct Attached)

Perhaps the simplest method of installing a plastic screen is to attach the screen directly to the
canny and then lower the entire assembly into the borehole. Screens can be attached to casing
by couplings that use solvent-welding procedures, adaptor rings that are fastened to the
casing, special locking couplings, and threaded connections.

After the casing and screen have been set in the hole, the screen may be filter packed and the
annular space above the pack then backfilled as far up the hole as possible. Placement of
backfill material prevents sudden slumping of the borehole walls before or during
development. The borehole should be backfilled carefully when plastic casing or screen are
used, because plastic casing does not have the collapse resistance of steel casing.

Bentonite can be placed in the annulus above the fill material. The casing is then grouted in
place with a neat-cement mixture, above the backfill and bentonite materials. The curing
temperance of the cement must not be so high that the casing deforms.

The use of plastic casing and screens for completing wells in consolidated rock with overlying
unconsolidated materials requires special techniques. When steel casing is used, a drive shoe
is normally seated in the rock and open-hole drilling is continued through the consolidated
aquifer. Because plastic casing cannot be driven, however, special packers are used to seal
the casing to the rock.

When using plastic materials, hydrostatic pressures exerted on both casing and screen must
be kept at a minimum during development. Development should begin slowly and gently
until all drilling fluid is removed from the annulus around the screen and water is flowing
freely into the screen. The casing and screen should never be "blown dry" with an air
compressor. If compressed air is used for development, start the development process well
above the screen and at first remove only small quantities of water.

8.5. OTHER METHODS

8.5.1. BAIL DOWN PROCEDURE

Under some conditions, it may be impossible or undesirable to pull back well casing to
expose the screen. For example, side-wall friction on casing by subsurface materials may
require too much pulling force, or movement of the casing may disturb the sanitary seal
around it. In other situations, the screen cannot be set by direct-attached methods because the
static water level may be so high and the aquifer materials so loose that the borehole may not
stand open. In these cases, the bail-down method of setting well screens may be used. The
The objective of the bail-down method is to remove sediment from below the screen so the screen will settle.

In the bail-down method, the casing is generally set before the bailing process can begin. When drilling by the rotary method, the casing must be fixed in a permanent position by grouting or some other sealing method. If cement grout is used, the plug is drilled Out of the lower end of the casing before starting the baildown procedure. When drilling by the cable tool or casing-driver methods, the casing is usually held firmly by side-wall friction.

The well screen, fitted with a bail-down shoe or an open sleeve at its Iowa end, is telescoped through the casing. A riser pipe may be welded or threaded to the top of the screen. If a bail-down shoe is used with special connection fittings, the screen is suspended on a string of pipe called the bailing pipe. The screen assembly is worked into the formation below the well casing by operating the bailer or drilling tools through the bailing pipe. To make the operation more efficient, the bailer should be as large as possible. Some drillers use an air-lift system to remove materials from below the screen. For this operation, an air line is lowered inside the bailing pipe and the bailing pipe then becomes the discharge or eductor pipe for air-lift pumping. The added weight of the bailing pipe assists in sinking the screen when the weight of the screen alone is insufficient.

When a screen is being bailed down, it is advisable to keep the work progressing as continuously as possible. If the work is stopped for some time, the formation sand may pack tightly around the screen and cause so much friction that the screen can no longer move downward.

Heaving conditions sometimes prevent complete removal of sediment to the bottom of the bailing pipe or well screen after the screen has reached the desired depth. Filling the bailing pipe with water will usually stop the heaving so the bottom can be cleaned out with a small bailer and the plug can be placed. If this is not effective, the bailing pipe and well screen can be filled with a heavier drilling fluid, or a weighted fluid such as salt water, to create greater pressure to counterbalance the tendency of the sand to heave.

When the screen has been bailed down to the desired depth, a plug is lowered or dropped through the bailing pipe to seat in the special extra-heavy nipple above the bail-down shoe. Occasionally, cement is used to plug the bottom of the screen. The string of bailing pipe is then disconnected by turning it several turns to the right to unscrew the left-hand joint at the top of the nipple, leaving the plug or cement and extra-heavy nipple to seal the bottom of the screen. In place of a left-hand threaded connection for the bailing pipe, some drillers prefer a lug or bayonet-type connection. After removing the bailing pipe, the packer at the top of the screen is expanded with a swedging tool and the well is ready for development.

### 8.5.2. WASH-DOWN METHOD

The casing is first set to the desired depth and grouted. After the grout has set, the cement plug at the bottom is drilled out. When the casing is in place, a pilot hole can be drilled to obtain formation samples.

A self-closing bottom fitting or backpressure valve is mounted in the bottom of the screen and connected by a left-hand thread to a string of pipe (usually drill pipe) used as the wash
line. The screen is lowered to the bottom of the casing and light-weight drilling fluid or water is then pumped through the wash line. A significant fluid loss can occur if water is used as the drilling fluid. Fairly high plump pressure and adequate volume are needed to produce a high-velocity jet of fluid through the self-closing bottom. The jetting action loosens and removes the sediment, and allows the screen to sink. No rotation is applied to the wash line or screen during the jetting operation. The sediment is brought up around the screen and comes up inside the casing with the return flow of the fluid. Some of the larger particles inevitably drop back inside the screen unless a temporary cover plate is mounted on the wash line to cover the top of the screen. Sediment in the screen can be removed by air-lift pumping, bailing, or circulation of driving fluid after the wash line has been disconnected.

When the screen reaches the bottom of the aquifer, clean water should be pumped through the wash line and then circulated at a reduced rate to remove filter cake that may have been deposited on the formation during the jetting operation. It is essential that the formation cave around the screen, holding it so the wash line, when turned to the right, disconnects at the left-hand joint just above the bottom fitting. Metal bars welded to the bottom of the screen help prevent it from turning when being disconnected.

### 8.6. INSTALLING WELL POINTS

Well points are often installed by some of the same methods already described for larger diameter well screens. For the pull-back method, casing is first set to the fun depth. A suitable packer is threaded to the top of the well point or riser pipe. After the well point has been dropped through the casing, the casing is pulled back to expose the screen to the water-bearing sediment. The drip tools may have to be placed on the well point to hold it down as the casing is pulled back. Many drilling contractors install 2-in stainless steel well points in Tin wells by this method.

Occasionally the pull-back method cannot be used because the friction on the pipe is so great that the force required to move the pipe might break it. In this case, a well point can be driven beyond the end of the casing into the sand formation below.

All the sediment in the casing is removed so the well point will not become sand-locked inside the pipe. If the sediment tends to heave, the casing is kept full of water while the screen is being set. The well point, with a self-sealing packer attached, is dropped through the casing. A driving bar, drill stem, or other similar tool is lowered to the top of the packer and alternately raised and dropped to drive the well point out the bottom of the casing. A driving weight of less than 500 lb and operated with a 2-ft stroke is recommended to minimize potential damage to the screen. Careful measurements must be made so the driller will know when the screen has been driven the correct distance. Use of a riser pipe is advised.

Some well points are manufactured with a drive plate mounted just above the point. The driving force is directed at the point, and the screen is pulled into place.

Two-inch well points can be set easily through hollow-stem augers once the auger-flight assembly has reached the proper depth. The screen is attached directly to the casing, and the swing is lowered inside the augers to the bottom of the borehole. The auger flights are then pulled back to expose the screen and casing. This method is particularly suitable in shallow, caving formations, and is often used to set monitoring wells.
8.7. REMOVING WELL SCREENS

Various circumstances arise that make it necessary to remove a screen assembly from a well. These situations include the following:

1. Inadequate yields at an original screen setting may force reinstallation at another depth.

2. In some areas, declining water tables may require that the well be deepened after some years of use.

3. Incrustation and cementation of the formation around the screen may require that the well be deepened because of the difficulty in chemically treating the screen in situ.

4. The screen must be replaced because corrosion damage is causing the well to pump sand.

CHAPTER 9.

DEVELOPMENT OF WELLS

Procedures designed to maximize well yield are included in the term "well development." Development has two broad objectives: (1) repair damage done to the formation by the drilling operation so that the natural hydraulic properties are restored, and (2) alter the basic physical characteristics of the aquifer near the borehole so that water will flow more freely to a well. These objectives are accomplished by applying some form of energy to the sheen and formation. Well development is confined mainly to a zone immediately adjacent to the well, where the formation materials have been disturbed by well construction procedures or adversely affected by the drilling fluid. In addition, the undisturbed part of the aquifer just outside the damaged zone may be reworked physically during development to improve its net oral hydraulic properties.

All new wells should be developed before being put into production to achieve sand-free water at the highest possible specific capacity. In addition, older wells often require periodic redevelopment to maintain or even improve the original yield and drawdown conditions. Maintaining a high specific capacity assures that the well will be energy efficient.

Another type of development, called aquifer development or stimulation, is done when the aquifer will not yield enough water even after well development procedures have been applied. This form of development is usually limited to semiconsolidated or completely consolidated formations. Well development techniques will be discussed before aquifer development procedures because they apply to every well, regardless of the geologic materials.

9.1. WELL DEVELOPMENT

Every type of drilling operation alters the hydraulic characteristics of formation materials in the vicinity of the borehole. These alterations often result in a severe reduction of the hydraulic conductivity close to the well bore. For example, many alluvial and most glacial
sand and gravel deposits are relatively young (less than 100,000 years) and have not been thoroughly compacted or cemented by geologic processes. These sediments usually are highly stratified; that is, the deposit consists of many layers, and in each layer the grains are all nearly the same size. These grains are loosely packed, and therefore the deposit has a large percentage of void space—commonly 25 to 35 percent.

If a well is drilled into a sand and gravel deposit with a cable tool rig or a rotary rig equipped with a casing driver, the repeated blows on the casing will change the loosely consolidated and naturally stratified condition of the deposit. Equal-sized grains will pack more closely together and smaller grains from above will move into the underlying void spaces. The result is a significant decrease in the porosity of the sediment and a drastic reduction in its natural hydraulic conductivity. The loss of stratification and the resulting mixing of the grain sizes is generally confined to the zone immediately around the borehole. To reduce this type of formation damage, some cable tool drillers sink the casing though the aquifer by bailing methods rather than by drilling and driving the casing.

The presence of clay in the formations being drilled or the addition of bentonite to the slurry to suspend the cuttings creates an additional need for development in holes drilled by the cable tool method. In many areas, thin clay lenses are irregularly inked with productive sand formations. During drilling, water is added to the cuttings periodically to create the slurry required for bailing. After bailing, some slurry will remain in the casing. When drilling is resumed and the bit protrudes out the end of the casing, some of the residual clay-rich slurry may enter underlying sand formations. In clay-poor formations, drillers add bentonite to form a slurry to suspend the cuttings so that the bailing operation is more efficient. The addition of bentonite may also be necessary to build the required hydrostatic head in the casing to contain heaving formations. As in direct rotary drilling, the bentonite prevents water from moving into the sand aquifers. One other problem occurs when casing is driven through sticky clays. The casing entrains some of the clay and carries it down the borehole, coating the face of potential aquifers. This clay must be removed to restore the ordeal hydraulic conductivity of the aquifer.

Both types of rotary drilling also cause damage to aquifers. In direct- and reverse-circulation rotary drilling, the action of the bit will cause some intermixing of sediments near the borehole, but this disturbed zone is generally not damaged as seriously as the disturbed zone created by the cable tool method. The most serious problem in rotary drilling occurs when drilling fluids containing clay enter the aquifer, often flowing many feet out from the borehole. In direct rotary drilling, drilling fluids usually consist of high-grade clay mixed with water. Once in the aquifer, the clay particles become fully hydrated and produce a powerful plugging effect. Even if clear water is used, naturally occulting clays exposed in the borehole can mix with the drilling fluid and plug the pore space of permeable formations. In most reverse rotary holes, fine sand and silt particles will also move into the aquifer because of the lack of a filter cake and the subsequent high fluid losses. Unfortunately, permeable sediments are more susceptible to defiling fluid penetration, and are thereby subject to the greatest potential loss in hydraulic conductivity.

Sloughing of weakly consolidated formations frequently occurs in rotary drilling operations when a sudden loss of drilling fluid momentarily reduces the hydraulic pressure in the borehole. Although the extra volume of material removed from the borehole may not seem
significant, the loss of stratification and subsequent mixing of the particle sizes can cause serious damage to the formation's original hydraulic characteristics.

The examples discussed above show that formation damage is unavoidable, regardless of which drilling method is used, and steps must be taken to restore the original hydraulic conductivity of the aquifer. All wells in both consolidated and unconsolidated formations should be developed until they are sand free when pumped at the desired rate. Techniques described below are applicable for all types of common aquifer materials, but the benefits are generally more substantial for unconsolidated sediment. Thus, the emphasis in this chapter will be on development of wells in formations where well screens are required. Development is an essential operation in the proper completion of any water well, however, because maximum specific capacity and well efficiency will rarely be reached without it.

Development procedures have the following beneficial purposes:

1. Reduce the compaction and intermixing of grain sizes produced during drilling by removing fine material from the pore space.

2. Increase the natural porosity and permeability of the previously undisturbed formation near the well bore by selectively removing the finer fraction of aquifer material.

3. Remove the filter cake or drilling fluid fern that coats the borehole, and remove much or all of the drilling fluid and natural formation solids that have invaded the formation.

4. Create a graded zone of sediment around the screen in a naturally developed well, thereby stabilizing the formation so that the well will yield sand-free water. Some stabilization of the formation can also be achieved in a filter peck well as long as the filter pack thickness is 8 in or less.

The ultimate result of proper well development is to provide sand-free water at maximum specific capacity.

9.2. FACTORS THAT AFFECT DEVELOPMENT

9.2.1. Well Completion Method

There are two major completion methods natural development and filter packing. The particular completion method is selected on the basis of the geologic character of the aquifer, the type of drilling rig, and the type of screen. The completion method determines to some degree the effectiveness of specific development methods.

In natural development, a highly permeable zone is created around the screen from materials existing in the formation. Creation of this zone is best understood by visualizing what happens throughout a series of concentric cylindrical zones in a sand aquifer surrounding the screen. In the zone just outside the well screen, development removes most particles smaller than the screen openings, leaving only the coarsest material in place. A little farther out, some medium-sized grains remain mixed with the coarse sediment. Beyond that zone, the material gradually grades back to the original character of the water-bearing formation. Finer particles brought into the screen in this process are removed by bailing or pumping.
Development work is continued until the movement of fines from the formation becomes negligible.

By creating this succession of graded zones around the screen, development stabilizes the formation and prevents further movement of sediment. After development, water moving toward the screen encounters sediment with increasing hydraulic conductivity and porosity. Improving the hydraulic conditions around the well will increase the specific capacity and efficiency. Thus, more water can be obtained from the well, and for any yield the cost of lifting the water to the surface will be minimized.

In filter packing, a specially graded sand or gravel having high porosity and permeability is placed in the annulus between the screen and the natural formation. It should be emphasized that development of the disturbed formation outside the pack is still mandatory to achieve maximum specific capacity.

9.2.2. Open Area and Slot Configuration

All development methods work best in wells equipped with screens having both maximum open area and the type of slot configuration that permit hydraulic forces exerted inside the well screen to be directed efficiency into the formation. Both factors are equally important in successful development. Screen open areas vary typically from a low of 1 percent for perforated pipe to more than 40 percent for continuous-slot, wire-wound screens. Screens with high open area can be developed more effectively because more of the development energy can reach the formation. Slot configuration also controls how much development energy reaches the formation, and the percentage of the formation that this energy can affect. Thus, more fine material can be removed more quickly if all the available energy can be directed at most or all of the surrounding formation.

9.2.3. Slot Size

Selection of the correct slot size for well screens is essential for successful well development. Slot openings are chosen to permit removal of the fine material from the formation. For naturally developed wells, it is common practice to select a slot width that retains about 40 percent of the sediment in the formation adjacent to the screen. For filter-packed wells, the slot opening is selected to retain about 90 percent of the filter pack material.

Slot size may govern the effectiveness of the development procedures. Removal of too much sediment may cause settlement of the overlying surface materials, which can have undesirable effects on the well and produce dangerous conditions for the drilling rig. On the other hand, when well screen openings are smaller than necessary, full development may not be possible and the well yield will be below the potential of the formation. Incomplete development can also lead to cementation or incrustation caused by abnormally high flow velocities and the corresponding pressure drop near the well bore.

9.2.4. Drilling Fluid Type

Clay and polymers are the two major drilling fluid additives used in rotary drilling. After a well is drilled, all drilling fluid must be removed from both the borehole walls and the formation by physical or chemical means. Although some polymeric drilling fluid additives
will break down naturally over time, it is recommended that they be broken down chemically and removed from the well at the time the well is completed.

The rate and effectiveness of drilling fluid removal depends not only on the type of additive used but also on the physical character of the aquifer, the depth of the well, and the weight and viscosity of the drilling.

9.2.5. Filter Pack Thickness

The thickness of the filter pack has considerable effect on development efficiency. This happens for two reasons. First, the filter peck reduces the amount of energy reaching the borehole wall. The thinner the filter pack, the easier it is to remove all the undesirable fine sand, silt, and clay when developing the web. Second, a filter pack is so permeable that water may flow vertically in the filter pack envelope at places where the formation may be partially clogged, rather than move into or out of the natural formation. To permit the transfer of development energy to the borehole wall, filter packs normally should be no more than 8 in thick and should be properly sized and graded according to design criteria.

9.2.6. Type of Formation

Different types of formations are developed more effectively by using certain development methods. For example, highly stratified, coarse-grained deposits are most effectively developed by methods that concentrate energy on small parts of the formation. In uniform deposits, development methods that apply powerful surging forces over the entire well bore produce highly satisfactory results. Other development methods that withdraw or inject large volumes of water quickly can actually reduce the natural hydraulic conductivity of formations containing a significant amount of silt and clay.

9.3. WELL DEVELOPMENT METHODS

Different well development procedures have evolved in different regions because of the physical characteristics of aquifers and the type of drilling rig used to drill the well. Unfortunately, some development techniques are still used in situations where other, more recently developed procedures would produce better results. New development techniques, especially those using compressed air, should be considered by contractors when they buy and equip a new rig. Any development procedure should be able to clean the well so that sand concentration in the water is below the maximum allowable limit set for the particular water use.

9.3.1. Overpumping

The simplest method of removing fines from water-bearing formations is by overpumping, that is, pumping at a higher rate than the well will be pumped when put into service. This procedure has some merit, because any well that can be pumped sand free at a high rate can be pumped sand free at a lower rate.

Overpumping, by itself, seldom produces an efficient well or full stabilization of the aquifer, particularly in unconsolidated sediments, because most of the development action takes place in the most permeable zones closest to the top of the screen. For a given pumping rate, the
longer the screen, the less development will take place in the lower part of the screen. After fine magenta has been removed from the permeable zones near the top of the screen, water entering the screen moves preferentially through these developed zones, leaving the rest of the well poorly developed and contributing only small volumes of water to the total yield. In some cases, overpumping may compact finer sediments around the borehole and thereby restrict flow into the screen. If more powerful agitation is not performed, an inefficient well may result.

There is another objection to overpumping that is commonly overlooked. Water flows in only one direction, toward the screen, and some sand grains may be left in a bridged condition, resulting in a formation that is only partially stabilized. If this condition exists and the formation is agitated during normal pump cycles after the well has been completed, sediment may enter the well if the sand bridges become unstable and collapse.

9.3.2. Backwashing

Effective development procedures should cause reversals of flow through the screen openings that will agitate the sediment, remove the finer fraction, and then rearrange the remaining formation particles. Reversing the direction of flow breaks down the bridging between large particles and across screen openings that results when the water flows in only one direction. The backflow portion of a backwashing cycle breaks down bridging, and the inflow then moves the fine material toward the screen and into the well.

A surging action consists of alternately lifting a column of water a significant distance above the pumping water level and letting the water fall back into the well. This process is called rawhiding. Before beginning the surging operation, the pump should be started at reduced capacity and gradually increased to full capacity to minimize the danger of sand-locking the pump. In the rawhiding procedure, the pump is started, and as soon as water is lifted to the surface the pump is shut off; the water in the pump column pipe then falls back into the well. The pump is started and stopped as rapidly as the power unit and starting equipment will permit.

Although overpumping and backwashing techniques are used widely, and in certain situations may produce reasonable results, their overall effectiveness in high-capacity wells is relatively limited when compared with other development methods. Other methods, as described below, are capable of removing more fine materials in less time and generally can produce higher specific capacities.
9.3.3. Mechanical Surging

Another method of development is to force water to flow into and out of a screen by operating a plunger up and down in the casing, similar to a piston in a cylinder. The tool normally used is called a surge block, surge plunger, or swab (Figure 9.1). A heavy bailer may be used to produce the surging action, but it is not as effective as the close-fitting surge block. Although some drillers depend on surge blocks for developing screened wells, others feel that this device is not effective and that it may, in some cases, even be detrimental because it forces fine material back into the formation before the fines can be removed from the well. To minimize this problem, fine material should be removed from the borehole as often as possible.

Before starting to surge, the well should be bailed to make sure that water will flow into it. Lower the surge block into the well until it is 10 to 15 ft beneath the static water level, but above the screen or packer. The water column will effectively transmit the action of the block to the screen section. The initial surging motion should be relatively gentle, allowing any material blocking the screen to break up, go into suspension, and then move into the well. The surge block (or bailer) should be operated with particular care if the formation above the screen consists mainly of fine sand, silt, or soft clay which may slump into the screen. As water begins to move easily both into and out of the screen, the surging tool is usually lowered in steps to just above the screen. As the block is lowered, the force of the surging movement is increased. In a well equipped with a long screen, it may prove more effective to operate the surge block in the screen to concentrate its action at various levels. Development should begin above the screen and move progressively downward to prevent the tool from becoming sand locked.
The force exerted on the formation depends on the length of the stroke and the vertical velocity of the surge block. The vertical velocity depends on the weight exerted on the block and the retraction speed. During retraction of the block continue the spudding motion to avoid sand locking the block in the casing. The speed of retraction and length of pull are governed by the physical characteristics of the rig.

Continue surging for several minutes, then pull the block from the well. Air may be used to blow the sediment out of the well if development is done with a rotary rig or if an air compressor is available. Sediment can be removed by a bailer or sand pump when a cable tool rig is used. The surging action is concentrated at the top of the screen, and this effect is accentuated if the lower part of the screen is continually blocked off by the sand brought in by the development process. In general, development can be accelerated if the amount of sediment in the screen is kept to a minimum. A sump or length of casing installed beneath the screen is helpful in keeping the screen free of sediment. Continue surging and cleaning until little or no sand can be pulled into the well. Total development time may range from about 2 hours for small wells to many days for large wells with long screens.

Occasionally, surging may cause upward movement of water outside the well casing if the washing action disrupts the seal around the casing formed by the overlying sediments. When this occurs, use of the surge block must be discontinued or sediment from the overlying materials may invade the screened zone.

Surge blocks sometimes produce unsatisfactory results in certain formations, especially when the aquifer contains many clay streaks, because the action of the block can cause clay to plug the formation. When this happens a reduction in yield occurs, rather than an increase. Surge blocks are also less useful when the particles making up the formation are angular, because angular particles do not sort themselves as readily as rounded grains. In addition, if large amounts of mica are present in the aquifer, the flat or tabular mica flakes can clog the outer surface of the screen and the zone around the screen by aligning themselves perpendicular to the direction of flow.

**9.3.4. Air Developing by Surging and Pumping**

Many drillers use compressed air to develop wells in consolidated and unconsolidated formations. The practice of alternately surging and pumping with air has grown with the great increase in the number of rotary drilling rigs equipped with large air compressors. In air surging, air is injected into the well to lift the water to the surface. As it reaches the top of the casing, the air supply is shut off, allowing the aerated water column to fall. Air-lift pumping is used to pump the well periodically to remove sediment from the screen or borehole, and is accomplished by installing an air line inside an eductor pipe in the well. Eductor systems are generally required for large diameter wells, when limited volumes of air are available, or when the static water level is low in relation to the well depth. Most rotary rigs, however, have sufficient air capacity to use the casing as the eductor for 6 to 12-in diameter wells.

For removing large volumes of water and cuttings, a surfactant is mixed into a small volume of water and then added to the airstream. The surfactant breaks up the water masses so they can be lifted to the surface at a rather low velocity (50 to 200 ft/min), thereby reducing air-volume requirements. During air development, however, surfactants are used only when
compressor capacity is insufficient to lift water to the surface. Therefore, the contractor must maintain uphole velocities in the range of 1,000 to 2,500 ft/min to achieve a reasonable discharge.

Generally, it is not possible to predict what uphole velocity is actually needed because of submergence factors, total pumping lift requirements, and the non-predictable way water will enter the borehole. It is virtually impossible to predict beforehand the uphole velocities required for air development procedures. In practice, the contractor ignores uphole velocity considerations and concentrates on the air volume needed to lift the water adequately.

9.3.5. Air Development Procedures

Air development procedures should begin by determining that groundwater can flow freely into the screen. Application of too much air volume in the borehole when the formation is dogged can result in a collapsed screen. To minimize the initial pumping rate, the air line and eductor (if used) can be placed at a rather shallow submergence. At this setting, even the introduction of large air volumes will produce only a moderate pumping rate and, therefore, will place only low collapse pressures on the well screen. Introduction of small air volumes at greater submergence also will produce low yields.

Once uninhibited flow into the screen has been established, the eductor pipe (if used) is lowered to within 5 ft of the bottom of the screen, assuming that sufficient pressure is available to overcome the static head. Development can also start near the top of the screen, depending on the preference of the driller. The air line is placed so that its lower end is up inside the eductor pipe at the proper submergence level. Before blowing any water or drilling fluid out of the well with a sudden large injection of air, the air lift should be operated to pump fluids at a reduced rate from the well.

Air is released into the line and the well is pumped until the water is virtually sand free. The valve at die air tank outlet is then closed, allowing the pressure in the tank to build. The actual pressure required will depend on the starting submergence; 43 psi is needed for each 100 ft of starting submergence. In the meantime, the air line is lowered so that its lower end is 1 ft or so below the eductor pipe. To initiate surging, the valve is opened quickly to allow air from the tank to rush suddenly into the well. This tends to drive the water outward though the well screen openings. Ordinarily, a brief but forceful head of water will also overflow or shoot from the casing and eductor pipe at the ground surface. When the air line is pulled up into the eductor pipe after the first charge of air has been released into the well, the air lift will again pump, thus reversing the flow (water flows into the well) and completing the surging cycle.

The well is pumped until the water clears up, and then another "head" of air is released with the air line set below the eductor pipe. To resume pumping, the air line is again lifted. Surging cycles are repeated until the water is relatively free of sand or other fine particles immediately after the screen has received an air blast. This indicates that development is approaching completion in the region near the bottom of the eductor pipe. The airlift assembly is then raised to a position about 5 ft higher and the same operations are repeated. In this way, the entire screen is developed in 5-ft intervals. From time to time, the air lift should be lowered to its original position near the bottom of the well and operated as a pump to clean out any sand that has accumulated inside the screen.
Under some conditions, the aquifer may become air locked when a large burst of air is injected into the screened area of the well. Certain kinds of formations are more prone to air locking, especially those formations that consist of stratified, coarse sand or gravel lenses separated by thin, impermeable clay layers. Aquifers with good vertical hydraulic conductivity are generally not affected. Surging with air usually does not lead to air locking. If some air becomes trapped in the aquifer, however, it may impede the flow of water toward the screen. In formations susceptible to air locking, surging with air should be avoided. Other procedures such as high-velocity jetting with water or air may be more suitable in formations where air trapping is a problem

9.3.6. High-Velocity Water Jetting Combined with Simultaneous Pumping

Although water jetting procedures are extremely effective in dislodging material from the formation, maximum development efficiency is achieved when waterjetting procedures are combined with simultaneous air-lift pumping or other pumping methods. This combination of development techniques is particularly successful for wells in unconsolidated sands and gravels. In water jetting, water is added to the well at a rate governed by the nozzle size and the pop pressure. The volume of water pumped from the well should always exceed the volume pumped in during jetting, because sediment removal is greatly enhanced with higher discharge. Thus, the water level in the well will be kept below static level and some water will move continuously from the formation into the well screen as the work proceeds. The steady movement of water into the well helps remove some of the suspended material loosened by the jetting operation. Ike air lift then pumps the sediment from the well before it can settee in the screen.

The jetting water is usually clean water hauled to the drill site. In instances where sufficient water supplies are unavailable, the contractor may use the water pumped from the well. To avoid damaging the high-pressure pump, jetting nozzles, and screen, however, the fine sand pumped from the well should be settled out in a tank or settling pit before this water is recirculated. To enhance the development process, chemicals such as polyphosphates are often added to the jetting water to help break up clays.

9.4. DEVELOPMENT OF ROCK WELLS

All drilling methods cause some plugging of fractures and crevices in hard-rock formations. In softer formations such as sandstone, the borehole wall may become clogged with finer material. In cable tool drilling, the bit action chips and crushes the rock and mixes it with water and other fine material to form a slurry. The pounding of the bit forces some of this slurry into the openings in the rock outside the borehole. When Wiling fluids are used in rock drilling, they also may plug crevices. Even airdrilling methods can blow large quantities of fine material into openings in the rock, causing drastic reductions in yield.

Any material that clogs openings in the rock aquifer must be removed by a development procedure. The full yield of the formation can be realized only if all the features and crevices can provide water to the well. Pumping alone sometimes pulls out the remaining sediment because the openings in rock formations are relatively large in comparison with the pores in a sand formation. However, many drillers have found that surging or other means of development for rock wells is needed to obtain maximum capacity.
9.5. AQUIFER DEVELOPMENT TECHNIQUES

In many parts of the world, the only available groundwater comes from bedrock. If the rock is massive, with few joints or faults, the volume of water available is often inadequate. In this type of aquifer, yields can be increased dramatically by applying one or more aquifer development techniques. Aquifer development, also called aquifer stimulation, can be thought of as a second levy of development which can increase well yields far beyond those obtained through typical well development. Aquifer development procedures in massive rock are usually cost effective. Some of these methods are described below. Under most circumstances, well development techniques are used before any aquifer development methods are initiated.

9.5.1. Use of Acid

Acid can be used for both well and aquifer development in limestone or dolomite aquifers and in some semiconsolidated aquifers that are cemented by calcium carbonate. Acid dissolves carbonate minerals and opens up the fractures and crevices in the formation around the open borehole, which is the intake portion of this type of well. Some of the acid, however, is forced into cracks and fissures much farther from the well bore. The acid dissolves some material naturally existing in the voids, thereby increasing the overall hydraulic conductivity of the aquifer.

9.5.2. Hydrofracturing

Hydrofracturing has been used successfully since 1947 in oil wells to overcome well bore damage, create reservoir fractures that improve well productivity, aid in secondary recovery techniques, and facilitate injection of brine and industrial wastes. More recently, this method has been used to increase the yields of low-production water wells in rock where joint systems or fracture systems are poorly developed or so tight that little water can move through them.

In hydrofracturing, high-pressure pumps are used to overcome the pressure of overlying rock and to inject fluids into newly opened fractures. For every foot of depth, the overburden pressure is usually equal to 1 psi. Therefore, at 200 ft the overburden pressure can be overcome with a pump capable of pumping fluids at pressures greater than 200 psi. Oil field hydrofracturing pumps can move fluids at pressures of 20,000 psi and more.

Cleaning the borehole walls before hydrofracturing is desirable because it removes drill cuttings, natural clays, or other mineral substances. This is done by mechanically brushing the walls with an oversized wire brush assembly or by jetting the walls with high-velocity water jets. Use of chemical additives such as diluted hydrochloric acid to remove calcium carbonate deposits, or sodium tripolyphosphate to remove clays, can greatly facilitate this prowess.

The following equipment is needed to apply the hydrofracturing technique: high pressure water pump; power-takeoff hydraulic pump, quick-coupled to a hydraulic motor, valve assembly dying flow to a packer inflation line and a water-injection line; one or more
inflatable packers; and compressed air source to inflate the packers and increase downhole pressure.

Hydrofracturing is accomplished by lowering an inflatable packer into a well and inflating it at a depth somewhat above the production zone. Thus, the production zone is isolated from the rest of the well. A fluid, usually water, is then pumped down through the packer into the well at pressures of 500 to 10,000 psi. About 800 to 1,000 psi is sufficient to fracture most formations that are already somewhat fractured; much higher pressures may be needed if the rock is massive with few cracks.

Hydrofracturing can increase water yield, improve reliability of water yield, reduce suspended sediment in the water, increase water storage in the well, and reduce pumping costs.

**9.6. CONCLUSIONS**

Patience, intelligent observation, and the right tools are required to develop a well correctly. Well development is not expensive, considering the often remarkable results that can be obtained in improving yields and eliminating sand pumping. Similarly, aquifer development is often overlooked as an effective way to increase yields substantially.

**CHAPTER 10. FIELD TESTING OF HYDRAULIC PARAMETERS**

Pumping tests may be conducted to determine (1) the performance characteristics of a well and (2) the hydraulic parameters of the aquifer. For a well-performance test, yield and drawdown are recorded so that the specific capacity can be calculated. These data, taken under controlled conditions, give a measure of the productive capacity of the completed well and also provide information needed for the selection of pumping equipment. An accurate test of a well before the pump is purchased pays for itself by assuring selection of a pump that will minimize power and maintenance costs.

The second purpose of pumping tests is to provide data from which the principal factors of aquifer performance—transmissivity and storage coefficient—can be calculated. This type of test is called an aquifer test because it is primarily the aquifer characteristics that are being determined, even though the specific capacity of the well can also be calculated. Aquifer tests will predict (1) the effect of new withdrawals on existing wells, (2) the drawdowns in a well at future times and different discharges, and (3) the radius of the cone of influence for individual or multiple wells. Aquifer test data are more valuable today because a better understanding of groundwater hydraulics now exists and new sophisticated methods of data retrieval and analysis have been developed.

An aquifer test consists of pumping a well at a certain rate and recording the drawdown in the pumping well and in nearby observation wells at specific times. There are two primary types of aquifer tests: constant-rate tests and step-drawdown tests. In the constant-rate test,
the well is pumped for a significant length of time at one rate, whereas in a step-drawdown test the well is pumped at successively greater discharges for relatively short periods. Data from both types of aquifer pumping tests can be analyzed to determine important hydraulic characteristics of an aquifer and the well. The results from properly conducted tests are the most important tool in groundwater investigations.

Measurements required for both well tests and aquifer tests include the static water levels just before the test is started, time since the pump started, pumping rate, pumping levels or dynamic water levels at various intervals during the pumping period, time of any change in discharge rate, and time the pump stopped. Measurements of water levels after the pump is stopped (recovery) are extremely valuable in verifying the aquifer coefficients calculated during the pumping phase of the test.

Although aquifer testing is more involved than well testing, the methods presented below for determining yields and measuring drawdown are used in both well and aquifer pumping tests. These methods and procedures apply primarily to constant-rate and step-drawdown aquifer tests.

10.1. CONDUCTING A PUMPING TEST

Pumping tests will not produce accurate data unless the tests are carried out methodically, carefully recording the time, discharge, and depth measurements. Certain preliminary steps should be taken to assure the reliability of pumping test data recorded during the actual test. For instance, several days before the test is to be conducted, the test well should be pumped for several hours to determine the following:

1. The maximum anticipated drawdown. (For most pumping tests, a major portion of the drawdown will occur in the first few hours of pumping.)

2. The volume of water produced at certain engine (pump) speeds and drawdown.

3. The best method to measure the yield.

4. Whether the discharge from the pump is piped far enough away to avoid recharge.

5. Whether the observation wells are located so that they exhibit sufficient drawdown to produce usable data.

Prior planning and experimentation with the equipment and personnel during preliminary testing can eliminate potential errors that may occur during the actual pumping test. Never begin the actual pumping test, however, until the water level in the aquifer has returned to the decimal (pretest) static level following preliminary testing. About 24 to 72 hours should be allowed, depending on the type of aquifer. Beginning a pumping test when the static water level is below normal may eliminate early data that show discharge or recharge boundaries. Without the early drawdown data, it may be impossible to obtain the correct transmissivity and storage parameters for the aquifer.

The accuracy of drawdown data taken during a pumping test depends on the following:
1. Maintaining a constant yield during the test.

2. Measuring the drawdown carefully in the pumping well and in one or two properly placed observation wells.

3. Taking drawdown readings at appropriate time intervals.

4. Determining how changes in barometric pressures, stream levels, and tidal oscillations affect drawdown data.

5. Comparing recovery data with drawdown data taken during the pumping portion of the test.

6. Continuing the test for 24 hours for a confined aquifer and 72 hours for an unconfined aquifer during constant-rate tests. For step-drawdown tests, 24 hours is usually sufficient for either type of aquifer.

10.1.1. Maintaining a Constant Discharge

Variations in engine (pump) speed are a major cause of erratic drawdown data. If a gasoline or diesel engine is used to drive the pump, the selected yield should be well below the maximum capacity of the engine. Engines running at full throttle tend to vary significantly in rpm, causing variations in the volume of water being pumped. Thus, it is good practice to restrict the engine speed to one-half to two-thirds of the maximum Ape In this range, the engine will run steadily, producing a more constant yield. Problems with varying rpm and yield can be virtually eliminated if an electric motor is used to drive the pump.

It is vital that a complete set of drawdown data be obtained once the pumping test commences. Therefore, for an aquifer test, the pump and power unit should be capable of operating at a constant pumping rate for at least 48 hours. In cases where the observation wells must be located at considerable distances from the pumped well, the pump must be capable of operating for at least several days. Pump failure during the test is expensive and even if the test is quickly resumed after repairs or refueling, the data are of questionable value. Therefore, the pump should be in good repair and the fuel supply should be adequate for the full term of the pumping test.

The pumping rate should be measured accurately and recorded periodically. Control of the pumping rate during testing requires an accurate device for measuring the discharge of the pump and a convenient means for adjusting the rate to keep it as nearly constant as possible. A valve in the discharge line of the pump provides the best control. The discharge pipe and the valve should be sized so that the valve will be from one-half to three-fourths open when pumping at the desired rate. Unnoticed changes in speed that result from varying line voltage on electric motors, or from variations in air temperature, humidity, or gasoline mixture on gasoline engines, cause less fluctuation of the discharge when the pump is working against the back pressure or head developed in Be partially closed valve. Changing the pumping rate by controlling the pump speed is generally unsatisfactory.
10.1.2. Direct Measurement Methods—Containers and Meters

A simple and accurate method for determining the pumping rate is to observe the time required to fill a container of known volume. For example, if it takes 30 seconds to fill a 55-gal barrel, the pump is delivering 110 gpm. This method is practical however, for measuring only relatively low pumping rates.

A commercial meter is more reliable when measuring large discharges. The dials on the meter show the total volume discharged through the meter up to the time of observation. Subtracting two readings taken exactly one minute apart gives the pumping rate. This is perhaps the easiest apparatus to use.

10.1.3. Orifice Weir

The circular orifice weir is the device used most often to measure the discharge rate from a high capacity pump. It will not measure the pulsating flow from a piston pump.

The orifice is a round hole with clean, square edges in the center of a circular steel plate. The plate must be 1/16 in thick around the circumference of the hole and is fastened against the outer end of a level discharge pipe so that the orifice is centered on the pipe. The end of the pipe must be cut squarely so the plate will be vertical. The bore of the pipe should be smooth and free of any obstruction that might cause abnormal turbulence. The discharge pipe must be straight and level for a distance of at least 6 ft before the water reaches the orifice plate. This approach channel should be longer if possible. The pipe wall is tapped midway between top and bottom with a 1/8-in or 1/4-in hole exactly 24 in from the orifice plate. Any burrs inside the pipe resulting from the drilling or tapping of the hole should be filed off.

A device called a piezometer (manometer) tube is fitted to a small hole to measure the water head (pressure) in the discharge pipe. The piezometer consists of a clear plastic tube 4 or 5 ft long. One end is connected to pipe fittings that are tapped into the hole in the discharge pipe. The nipple, which is screwed into the tapped hole, must not protrude inside the pipe. A scale is fastened to a support so that the vertical distance from the center of the discharge pipe up to the water level in the piezometer tube can be measured. The water level in the piezometer tube indicates the pressure head in the approach pipe when water is being pumped through the orifice.

Besides making the parts accurately and setting up the device correctly in the field, two precautions must be taken to assure good results. The diameter of the orifice should be less than 80 percent of the inside diameter of the pipe that serves as the approach channel.

The piezometer tube must be completely free of air bubbles, obstructions, or constrictions when reading the pressure head. Air bubbles can be eliminated by lowering the tube between readings so that water flows from it.

The gate valve used to control the pump discharge should be installed at least 10 pipe diameters in the piezometer connection.

10.1.4. Weirs and Flumes
Another method used to measure flow from a well is by means of a constriction placed in a discharge channel originating at the well head. In most cases, the drilling contractor can channelize the flow from a pumping well. A calibrated constriction placed in the channel changes the level of the water in or near the constriction. By knowing the dimensions of the constriction, the rate of flow through or over the constriction will be a function of the water level. A simple depth determination near the constriction provides a discharge measurement.

10.1.5. Drill-Stem Testing

Drill-stem testing is routinely done in the oil industry to check on the potential yield from a certain formation just after it has been drilled. This type of test is also done by some contractors in the water well industry who have equipped themselves with the necessary tools. A properly run drill-stem test will provide water quality information from the horizon of interest, an estimate of the yield, and an indication of downhole pressures during pumping and periods of no pumping.

In a drill-stem test a special tool is attached to the drill string. Packers are installed at one or both ends of the tool so that the intake portion of the tool is isolated from the drilling fluid column in the borehole. The tool is also equipped with pressure sensors. After the tool is lowered to the selected formation, multiple cycles of pumping and non-pumping provide information on pressure, yield, and water quality. Highly sophisticated methods of data analysis are used in the oil industry to evaluate results from drill-stem tests, but these methods are not applicable to drill-stem tests for water wells. Data can simply be used "as is" because boreholes are considerably shallower.

10.2. MEASURING DRAWDOWN IN WELLS

10.2.1. Observation Wells

Drawdown data can be taken from both the pumping well and appropriately placed observation wells, but the accuracy of data taken from the pumping well is usually less reliable because of turbulence created by the pump. Thus, at least one observation well should be used when practicable. Furthermore, drawdown data from an observation well are required to calculate the storage coefficient accurately, whereas transmissivity values may be calculated on the basis of drawdown data taken from either a pumping well or observation well.

Observation wells should be just large enough to allow accurate and rapid measurement of the water levels. Small diameter wells are best, because the volume of water contained in a large diameter observation well may cause a time lag in drawdown changes.

When observation wells are too close to the pumped well, the drawdown readings may be affected by the stratification of the aquifer. Stratification distorts the distribution of hydraulic head and drawdown in the vicinity of the pumped well during the aquifer test. At any moment after test pumping is started, the drawdown in a series of observation wells placed at a given distance from the pumped well may vary if the screens are set at different depths within the aquifer. These variations in drawdown become less as time of pumping increases. The
distorted pattern of drawdown caused by stratification is eliminated at distances equal to three to five times the aquifer thickness.

For unconfined aquifers, observation wells should be placed no farther than 100 to 300 ft from the pumped well. For thick confined aquifers that are considerably stratified, observation wells should be placed within 300 to 700 ft of the pumped well. Locating the wells too far away is not good practice because the pumping test must be continued for a longer time to produce sufficient drawdowns at the most distant points, and small measurement errors may be a significant percentage of the total drawdown in the observation well.

Screens for observation wells should be installed at about the same depth as the central passion of the screen in the production well. If this procedure is followed, the reduction in pressure or water level at the observation well will usually occur within moments of its occurrence in the pumping well (assuming the observation well is spaced at the collect distance from the pumped well). Occasionally, observation wells are terminated in strata above or below the one tapped by the pumped well to see if there is any hydraulic interconnection between the formations. Naturally the response of these observation wells to pumping may be delayed significantly, depending on the degree of hydraulic connection.

The appropriate number of observation wells depends upon the amount of information desired. The data obtained by measuring the drawdown at a single location outside the pumped well permit calculation of the average hydraulic conductivity, transmissivity, and storage coefficient of the aquifer. If two or more observation wells are placed at different distances, the test data can be analyzed by studying both the time-drawdown and the distance-drawdown relationships. Using both these analytical methods provides greater assurance that the calculated transmissivity and storage coefficient values are correct.

Before starting the pumping test, a complete program for depth-to-water measurements must be laid out in advance. It is not necessary to make the measurements in all the wells simultaneously. The watches used for timing the measurements, however, should be synchronized so that the time of each reading can be referenced to the exact minute and hour that pumping is started.

Using measurement devices that will give quick and accurate results, drawdown should be measured in the pumping well and all observation wells.

The gauges ordinarily used to measure the depth of water in a well are:

1. Pressure gauge—reading in pounds per square inch (psi).
2. Altitude gauge—reading in feet and fractions of a foot.
3. Vacuum gauge—reading in inches of vacuum, or difference in pressure between mercury under atmospheric pressure and water being pumped.

Well driller should become familiar with these gauges and their applications. They are comparatively simple and easy to use, but for important tests they should be calibrated with master gauges. Readings will be more accurate if the range of the gauge only slightly exceeds...
die range of the anticipated drawdown values. Pressure gauges are most often used by drilling contractors.

In English engineering units, the depth of a water column is measured in feet or pounds per square inch (psi). For example, when using a pressure gauge, the readings are in psi and must be multiplied by 2.31 to convert to feet of water. To convert a reading in feet to one in psi the reading is multiplied by 0.433. Table 10.1 contains conversions for the typical types of readings taken during a test.

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<th>Unit</th>
<th>psi</th>
<th>ft of water</th>
<th>m of water</th>
<th>inches of mercury</th>
<th>atmospheres</th>
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<td>2.31</td>
<td>0.704</td>
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</tr>
<tr>
<td>1 ft of water</td>
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<td>0.882</td>
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<tr>
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Table 10.1. Conversions for Typical Readings Taken During a Pumping Test

The most common method of measuring water levels in a pumping well is the air-line method, which works on the principle of measuring the air pressure needed to force the water out of a tube that extends down the well to some known depth below the water level. The air pressure is then converted to an equivalent column of water above the bottom of the air line. This method is not nearly as accurate as the steel tape or electric probe, but it is usually sufficient and the most practical method for use in a pumping well.

Figure 10.1 shows the installation of an air line in a well for the purpose of determining the depth to water. The device works on the principle that the air pressure required to push all the water out of the submerged portion of the tube equals the water pressure of a water column of that height. If this pressure is expressed in feet of water, the depth to water can be calculated. The air line consists of a small-diameter plastic (PVC) pipe or tube of sufficient length to extend from the top of the well to a point several feet below the lowest anticipated water level to be reached during the test. The exact length of the air line must be measured as it is placed in the well. If flexible tubing is used, steps must be taken to assure that the tubing hangs vertically and does not spiral inside the well casing. The air line and connections at the ground surface must be completely air tight. Before starting the pumping test, the line is prepressurized and the gauge pressure recorded. During pumping, the pressure in the line is reduced; this pressure drop can be directly related to feet of water level fall.
For example, suppose the distance from the top of the well casing to the lower end of the air line is 95 ft. As air is pumped into the line, assume that a maximum reading of 46 ft is reached on the gauge. The depth to water is then the difference between 95 and 46, or 49 ft. This is the static water level. After the pump is started, the water level in the well drops, the submerged length of the air line decreases, and the pressure indication on the gauge drops accordingly. A gauge reading of 34 ft, for instance, would mean that the submerged length of the air line has decreased by 12 ft (46-34) and the depth to water has changed to 95 minus 34, or 61 ft. This indicates a drawdown of 12 ft below the static water level. If the gauge reads in psi, each leading must be multiplied by 2.31 to convert it to feet of water. For example, a reading of 15 psi corresponds to a pressure head of 34.6 ft of water.

The air-line method is generally not accurate enough for use in observation wells during an aquifer test, but it is the most practical means for measuring water levels in a pumped well. Because measuring depths during pumping tests is labor intensive, automatic depth indicators have been developed.

The most widely used automatic water level measuring device is the mechanical, float-actuated, drum recorder. This device can be geared to provide a continuous water level record for periods of time ranging from 4 hours to one month, and can record water levels with an accuracy of 0.001 ft. A less common device relies on an electronically actuated pressure transducer placed in the well at some depth below the water level. Transducers
measure feet of water (hydraulic head) above the transducer. The amount of head over the transducer is automatically printed out for any selected time after pumping commences; the time and feet of head can be printed on a strip chart. With proper calibration, this device will also measure water levels accurate to 0.005 ft.

In automated drawdown measuring systems, transducers are placed in each well and electrically connected to analyzer, computer, and printer-plotter equipment.

### 10.2.2. Recommended Time Intervals for Measuring Drawdown During a Constant-Rate Pumping Test

All watches of observers should be synchronized before the test begins; times should be recorded to the nearest 10 seconds. Water-level measurements for the pumped well should be recorded at the times suggested in Table 10.2. Of course, drawdown in wells more distant from the pumping well will not occur immediately. Drawdown readings in the observation wells should be taken at the intervals recommended in Table 10.3.

<table>
<thead>
<tr>
<th>Time Since Pumping Started (or Stopped) in minutes</th>
<th>Time Intervals Between Measurement in minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 0 - 10</td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>10 - 15</td>
<td>1</td>
</tr>
<tr>
<td>15 - 60</td>
<td>5</td>
</tr>
<tr>
<td>60 - 300</td>
<td>30</td>
</tr>
<tr>
<td>300 - 1440</td>
<td>60</td>
</tr>
<tr>
<td>1440 - termination of test</td>
<td>480 (8 hr)</td>
</tr>
</tbody>
</table>

**Table 10.2. Recommended Time Intervals for Measuring Drawdown in the Pumped Well During a Pumping Test**

<table>
<thead>
<tr>
<th>Time Since Pumping Started (or Stopped) in minutes</th>
<th>Time Intervals Between Measurements in minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 60</td>
<td>2</td>
</tr>
<tr>
<td>60 - 120</td>
<td>5</td>
</tr>
<tr>
<td>120 - 240</td>
<td>10</td>
</tr>
<tr>
<td>240 - 360</td>
<td>30</td>
</tr>
<tr>
<td>360 - 1440</td>
<td>60</td>
</tr>
<tr>
<td>1440 - termination of test</td>
<td>480 (8 hr)</td>
</tr>
</tbody>
</table>

**Table 10.3. Recommended Time Intervals for Measuring Drawdown in the Observation Well(s) During a Pumping Test**
Early test data are extremely important, and as much information as possible must be obtained in the first 10 minutes of pumping for every observation well. The reason for this is that, as the cone of depression moves outward from the well, it may encounter inhomogeneities in the ground which cause either an acceleration or a deceleration of drawdown with increasing time. Any unusual event (stoppage of pump, onset of weather change, or passage of a train) should be noted, along with the time it occurred.

Ideally, pumping tests should be continued until equilibrium is reached, that is, until the cone of depression stabilizes. In practice this is rarely possible. In confined aquifers, the cone of depression spreads rapidly because no actual dewatering takes place; only a pressure reduction is occurring outward from the well. Thus, 24 hours is usually sufficient to record enough reliable data for confined aquifers. To gain enough information for unconfined aquifers, 72 hours are usually required to dewater the materials within the cone of depression, because of the slow downward percolation of water in many stratified deposits. This time can be reduced if equilibrium conditions are established before 72 hours have elapsed. In no event should pumping tests be terminated prematurely, however, because the limited data collected may not reveal the true nature of the aquifer.

Barometric or tidal changes can influence drawdown data. For example, a barometric pressure change of 1 in of mercury can result in a rise or fall of up to 1 ft in the potentiometric surface for confined aquifers that have high barometric efficiency. Barometric efficiency refers to the aquifers ability to transmit changes in atmospheric pressure. Record the nature and time of any weather changes on the drawdown data sheet. Unusually high or low oceanic tides can also affect drawdown data in wells near coastlines.

10.2.2.1. Recovery Data

Whenever possible, recovery data should be taken to verify the accuracy of pumping data. Often, the recovery data will be more reliable because no pumping is required and any previously inexperienced personnel will have learned paper measurement techniques by the time recovery data can be taken. Recovery measurements should be recorded with the same frequency as those taken during the pumping portion of the aquifer test.

CHAPTER 11.

PUMPS AND PUMPING

The primary function of a pump is to add hydraulic energy to certain volumes of fluid. This is accomplished when the mechanical energy imparted to the pump Cam a power source is transferred to the fluid, thereby becoming hydraulic energy. Thus, a pump serves to transfer energy from a power source to a fluid, thereby creating flow or simply creating greater pressures on the fluid. Pumps can serve many different purposes. These include raising a liquid from one level to another, moving a fluid through a pipeline imparting a high velocity to water, and moving liquids against a resistance.

A pump can impart three types of energy to any fluid: head, pressure, and velocity. The amount of each type of hydraulic energy will vary from place to place in a system. For example, when water is at rest in a storage tank, it possesses head energy but no velocity or
pressure energy. Once water starts to flow from the storage tank, it has head, pressure, and velocity energy. As water flows from the end of a pipe or hose, the head and pressure energy are transformed to velocity energy alone.

Pumps are installed in water wells to lift the water to the ground surface and deliver it to the point of use. Many types and sizes of pumps are available, ranging in power from a fraction of one horsepower to several thousand horsepower. In the water well industry, pumps are classified generally into two groups: shallow-well pumps and deep-well pumps. A shallow-well pump is mounted at ground level and removes water from the well by suction lift. A deep-well pump is installed within the well casing, with the pump inlet submerged below the pumping lever. The deep-well pump must be used for any well where the pumping level is below the limit of suction lift (approximately 20 to 25 ft).

A general method of classifying pumps is to divide them into two groups: positive displacement and variable displacement. Although positive displacement pumps are used extensively in groundwater monitoring wells, in hand-pump-equipped wells, and in wind-powered wells, they are used rarely for domestic or large-capacity water wells. Thus, variable displacement pumps will be discussed first in this chapter because of their wide use in the water well industry.

11.1. VARIABLE DISPLACEMENT PUMPS

The distinguishing characteristic of variable displacement pumps is the inverse relationship that exists between the rate at which they deliver water and the head against which pumping takes place. For example, as the head increases, the rate of pumping decreases.

The pumping rate in any variable displacement pump is dependent upon the pressure or number of feet of lift against which the pump is operating. A general term for this pressure is head or static lift, and can be calculated by adding the pumping water level in the well to the lift required above the discharge point.

The lift required, however, is only a part of the total head that the pump would be operating against. Friction losses that occur in the pipe during pumping must also be added to the lifting head to determine dynamic head or total dynamic head. These friction losses are sometimes referred to as the friction head. Friction head represents the combined head losses in the pipe, valves, and other fittings caused by flow velocity, viscosity, and specific gravity of the fluid. The major types of variable displacement pumps are:

1. Centrifugal pumps
   a. Suction lift
   b. Deep-well turbine
   c. Submersible turbine
2. Jet pumps
3. Air-lift pumps

11.1.1. CENTRIFUGAL PUMPS

The basic principles of the centrifugal pump were recognized about 300 years ago. In the latter part of the 19th century, the steam turbine and the electric motor were developed as
suitable sources of power for pumps. The centrifugal pump then became popular as a pumping device. It is capable of delivering large quantities of water, against high as well as low head conditions, with good efficiency.

There are many design variations in centrifugal pumps. Originally designed as a pump to be located at or near ground surface for suction-lift or booster service, it soon was adapted to installation under water in wells, first by long shaft extensions in large caissons (vertical turbine), and later in compact form as the familiar deepwell (submersible) turbine pump.

The basic principle of centrifugal pumping can be illustrated by considering the effect of swinging a pail of water around in a circle at the end of a rope. Centrifugal force causes the water to press against the bottom of the pail rather than run out at the open end. If a hole were cut in the bottom, water would discharge through the opening at a velocity related to the centrifugal force. If an airtight cover were put on the pail a partial vacuum would be created inside the pail as water is discharged. This vacuum could draw additional water into the pail through an intake pipe connected to the cover if the lift were not too great.

11.1.2. CENTRIFUGAL PUMP DESIGN

There are five distinct types of centrifugal pumps, each of which can be modified, within limits, by changing the impeller design to provide different operational characteristics. An impeller is the rotary element in a centrifugal pump that imparts a high velocity to the water. The five pump types are:

1. Turbine (diffusers
2. Volute
3. Mixed flow
4. Axial flow (propeller)
5. Regenerative

Water well contractors generally use only the turbine pump. In this type of pump, the impeller is surrounded by diffuser vanes that provide gradually enlarging passages in which the velocity of the water leaving the impeller is reduced, thereby increasing the pressure. Because so many turbine pumps are used in deep-lift installations, the term "turbine pump" is often misapplied to all centrifugal pumps used in these installations.

The volute pump differs from the turbine pump in that there are no diffuser vanes and the impeller is housed in a spiral-shaped case. Similar to a turbine pump, the velocity of the water is reduced upon leaving the impeller, thus transforming velocity head to pressure head.

Mixed-flow centrifugal pumps use both the centrifugal force generated by an impeller and some lifting action produced by a propeller to move water. Mixed-flow pumps are used extensively for large-capacity installations operating against relatively low heads.

Axial-flow pumps are often called propeller pumps because they produce most of the flow by the lifting action of propellers. They are used almost exclusively for large-capacity pumping against extremely low heads.

11.1.3. SEMI-OPEN IMPELLERS
Semi-open impellers have a series of curved but partially unsupported vanes that are enclosed at the top only. Commonly, this type of impeller is used for pumping liquids carrying some solids. Lack of close clearance or restricted passageways is desirable to prevent plugging.

11.1.4. CLOSED IMPELLERS

Closed impellers have vanes that are enclosed at the top and bottom. This provides a controlled area to channel water through the impeller. Flow enters the eye of the impeller and follows the enclosed vane into the next assembly. The tolerances between the outside skirt of the impeller and the vertical edge of the bowl assembly are quite close and do not allow much leakage past the impeller if placed properly in the bowl.

11.1.5. CAVITATION

Cavitation is a condition that occurs when the pressure acting on a stream of liquid falls to or below the vapor pressure of that liquid. When water enters the eye of the impeller in a turbine pump, the velocity increases, thereby causing a corresponding reduction in pressure. If the pressure falls below the vapor pressure (at the liquid's temperature), the liquid will begin to vaporize, and part of the flow through the pump will consist of vapor pockets. At some point, the liquid will reach an area of higher pressure, causing the pockets to collapse at such a rapid rate that a rumbling noise can be heard. The collapse of these pockets is so violent that it causes pitting on the impeller and bowl surface.

In propeller pumps, water from the larger inlet area entering the throat ahead of the propeller accelerates rapidly. If the head is increased too much, the capacity is reduced to the point where insufficient fluid exists to fill the space between the propeller vanes. Vacuum pockets develop along the vanes momentarily, but almost instantly the space is filled as the liquid crashes against the propeller vanes. The force of the liquid hitting the vane surface can cause severe pitting of the vane.

Cavitation is generally indicated by fluctuations or reductions in yield, erratic power consumption (fluctuating amperage readings), and noisy operation.

11.1.6. SUCTION-LIFT PUMPS

Suction lift is developed by creating a negative pressure at the pump intake. Atmospheric pressure on the free surface of water in a well forces water up into that part of the pump where the reduced pressure has been developed. The maximum - suction lift is limited by four factors: atmospheric pressure, vapor pressure, head losses attributable to friction, and NPSH requirements of the pump itself.

Atmospheric pressure varies with atmospheric conditions and elevation. For practical purposes, it is assumed that the Earth's atmosphere normally exerts a pressure of 14.7 psi at sea level—the equivalent of about 34 ft of water heat Under normal conditions at sea level, therefore, it might be assumed that a water colony would be lifted 34 ft if a perfect vacuum could be produced by a pump.
11.1.7. DEEP-WELL TURBINE PUMPS

The centrifugal pump was designed originally as a suction-lift pump, although it was soon adapted for water wells where suction lift was not possible by extending a shaft extension from the aboveground driving unit to the impeller assembly. Today this pump is known as the deep-well turbine pump.

11.1.8. VERTICAL TURBINE PUMPS

The pumping assembly of a vertical turbine pump consists of one or more impellers housed in a single- or multi-stage unit called a bowl assembly. Each stage provides a certain amount of lift; a sufficient number of stages (bowl assemblies) are assembled to meet the head requirements of the system. When designing a pump system, the number of stages needed are proportional to the head and horsepower requirements, whereas the discharge rate and efficiency remain constant. The impellers are suspended on a vertical line shaft (drive shaft) that is housed within the pump column which conducts the water to the surface. The size of the outer column is selected on the basis of the pumping rate.

Individual sections of the pump column are generally 10 or 20 ft in length. The overall length of column is determined by the pumping water level.

11.1.9. SUBMERSIBLE PUMP

Submersible pumps have bowl assemblies that are the same as those of vertical turbine pumps. The motor, however, is submerged and is directly connected to and located just beneath the bowl assembly. Water enters through an intake screen between the motor and bowl assembly, passes through the stages, and is discharged directly through the pump column to the surface.

Submersible motors are extremely compact and generally do not withstand overheating and fluctuations in voltage. They are cooled by water passing by the motor casing and into the intake of the pump, so a free flow of water must be maintained. Overheating may occur if the well has cascading water or if the pump intake is set into a sump (casing below the screen).

Submersible pumps have several advantages:

1. The motor is directly coupled to the impellers.
2. It is easily cooled because of complete submersion.
3. Ground surface noise is eliminated.
4. The pump can be mounted in casings that are not entirely straight.
5. A pump house is not necessary if a pitless adaptor (underground discharge) is used.

Disadvantages of submersible pumps are:

1. Electrical problems caused by submerged cables and splicing of cables to the motor.
2. Overall efficiency is generally lower.
3. They cannot tolerate sand pumping (will sand lock).
4. Motor is less accessible for repairs.
5. They cannot tolerate voltage fluctuations without proper protection.

11.1.10. JET PUMPS

Jet pumps are used in many domestic wells and are a combination of a centrifugal pump and a nozzle-venturi arrangement. Water discharges under pressure through a nozzle inserted in the pipe conveying the water. The nozzle is shaped so that it smoothly, but rather abruptly, reduces the area through which the flow must pass, thus increasing the velocity of flow. In accordance with the Bernoulli law, the water pressure in a pipe decreases in direct relation to any increase in the flow velocity, and vice versa. That is, if the velocity increases at any point because of a reduction in area, as would occur near the nozzle, the pressure decreases proportionately at that point.

If the discharge velocity at the nozzle is great enough, the pressure at the nozzle will be lowered sufficiently to draw water into the venturi assembly through an opening at this point, and this water is added to the total volume of water flowing beyond the nozzle. The gradual enlargement in the venturi tube to the full diameter of the pipe reduces the velocity with a minimum of turbulence, and pressure in the pipe is recovered, minus the head loss caused by friction. The prime mover in a jet pump is a centrifugal pump, which produces the flow to the nozzle and maintains the combined flow through the intake pipe beyond this point. This combined flow is composed of the recirculating water and the water picked up at the nozzle from the well. The additional increment of water obtained from the well continues past the control valve and goes into use or storage, while the volume required for producing the flow is recirculated through the pressure line.

Jet pumps are inefficient when compared with ordinary centrifugal pumps, but this is not necessarily objectionable in domestic installations, because of other favorable features, such as:

1. Adaptable to small wells, down to 2-in inside diameter in deep-lift installations.
2. All moving parts are accessible at the ground surface.
3. Simple design combined with relatively low equipment and maintenance costs.
4. Capable of being installed with the moving parts offset from the well.

11.1.1 1. Priming Centrifugal Pumps

Priming is necessary to expel air from centrifugal pumps. Many devices and procedures are used to obtain and maintain a primed condition in centrifugal pumps; the literature describing them is fairly extensive. In general, however, all involve one or a combination of the following: (1) a foot valve to hold water in the pump, (2) a means for venting to dispose of entrained air, (3) an auxiliary pumping device to partially fill the centrifugal pump and intake
line with water, (4) connection to an outside source of water under pressure for filling the pump, and (5) use of self-priming construction. Self-pumping construction retains water for priming in an auxiliary chamber which is integrated into the pump structure in such a way that entrained air is exhausted as the pump circulates the priming water.

11.2. POSITIVE DISPLACEMENT PUMPS

Positive displacement pumps discharge the same volume of water regardless of the head against which they operate, although in practice this is not quite true, because some water slips past operating parts. This type of pump must be powered to meet maximum load based on its discharge capacity and the greatest head under which it will operate. When used in a water system, the rate of discharge is essentially the same at both low and high pressure, but the input power varies in direct proportion to the pressure.

There are many designs of positive displacement pumps, but the types used most are:

1. Rotary pumps
2. Peristaltic pumps
3. Piston (reciprocating) pumps

11.2.1. Rotary Pumps

The rotary pump is widely used because there are many design modifications for special applications. Most applications are of the suction-intake type, except when the pump is used for booster purposes in conjunction with another pump to increase the pressure or to pump hot water or other liquids having high vapor pressure; in this case, the pump operates under positive intake pressure. Common designs use cogs or gears, and rigid vanes or flexible vanes; none of these pumps require valves.

The original rotary pump was designed using gears, and is simple in principle and construction. It consists of a plain housing with inlet and outlet ports, and openings for shafts which carry the driver gear and a driven or idler gear. The gears are fitted closely in the housing, and mesh with minimum clearance. When rotated, the gears squeeze the water from between the teeth as they mesh together, bringing in a replacement supply of water along the outer surface of the housing at the inlet side of the moving teeth of the gears.

A typical rigid-vane rotary pump has a series of dividers or vanes fitted into a slotted rotor. When rotated, these vanes move radially to conform to the contour of the pump housing, which is eccentric in comparison with the rotor, so that the water is pushed from the pump in a continuous flow ahead of the vanes. Water moves into the housing behind the vanes because a partial vacuum is created. A flexible-vane rotary pump has blades that bend to provide the change in displacement volume which forces the water along its path.

11.2.2. Piston Pumps

The simplest arrangement for a piston pump is the single-action pump shown schematically in Figure 11.1. When the piston is drawn upward, the check valve in the piston is closed by gravity and the water pressure above it. A lowering of pressure is therefore produced below
the moving piston. Water flows through the intake valve into the pump cylinder as a result of the pressure differential caused by the stroke of the piston.

![Diagram of a piston pump](image)

**Figure 11.1. A single-acting piston pump, suspended on discharge pipe, can be installed at almost any depth in small-diameter wells.**

As the piston moves downward, the intake valve closes when the pressure above it exceeds the pressure below it, and the discharge valve opens when the pressure below it exceeds that above it. Thus, water trapped in the cylinder during the downstroke of the piston is forced upward into the discharge pipe on the next upstroke.

Because water is virtually incompressible, the piston moves the same volume of water at each stroke, regardless of pressure, less any water that slips past the piston and valves. Piston pumps must be powered to meet the maximum pressure application, and protection against breakage must be provided by some device, such as a pressure-relief valve, in case the pressure switch or other control mechanic fails.

The basic principles just described apply to all piston pumps; however, there are many design modifications that adapt these pumps to specific uses. Double-action pumps, for example, are constructed with piston and valves arranged so that water is pumped on both inward and outward movement of the piston. These are most commonly suction-lift pumps, but are also available for pressure-intake installations in wells. Duplex and triplex pumps consist of two or three pistons, respectively, and are designed to pump a continuous stream with minimum pulsation, often against high pressure. These pumps are often utilized for pumping drilling fluid and grout.
11.2.3. Priming Positive Displacement Pumps

Positive displacement pumps must be primed only to the extent necessary to stop leakage past pistons, valves, or other working parts. They have the capability to move and compress most fluids, including air, so that water (or another liquid) can be drawn into the pump without priming.

11.3. PUMPS USED TO CIRCULATE DRILLING FLUID

Two basic types of pumps are used to circulate drilling fluid—reciprocating and centrifugal. The reciprocating pump can be either single or double acting. Either of these designs can be arranged in parallel by operating the pistons from a common crankshaft. They are then referred to as simplex (1 cylinder), duplex (2 cylinders), and triplex (3 cylinders) pumps. Additional pumps can be added if more volume must be moved.

Optimum operating conditions for reciprocating mud pumps are assured if:

1. The suction piping is as short as possible.
2. The diameter of the suction line is large enough so the fluid velocity is less than 3 ft/sec.
3. An intake strainer with two to four times the intake area of the suction hose is installed at the end of the suction line.
4. The diameter of the discharge pipe is large enough so that the fluid velocity is less than 5 ft/sec.
5. The pump operates under proper net positive suction head conditions.
6. A surge suppressor is installed in the suction line as close to the pump as possible.
7. The pump is selected for a higher discharge than the expected demand.
8. Priming time does not exceed 30 seconds in order to minimize friction damage to the plunger.

The operation of a centrifugal pump is described earlier in this chapter. When used for mud pumps, they are designated by the size of the discharge and suction lines and the size and rotation direction of the impeller. Unlike reciprocating designs, the rate of fluid delivery for a centrifugal pump is variable depending on the pressure in the borehole. At maximum discharge, the pressure head is usually about two-thirds the pressure obtainable at zero fluid delivery. The actual drilling fluid discharge is a function of the rotation speed, fluid efficiency, and the available power, as well as the downhole pressure. A centrifugal pump is most suitable for low-pressure, high-volume situations, whereas reciprocating pumps are ideal for high-pressure, low-volume applications. The basic difference in the operational characteristics of the two mud pump types is illustrated in Figure 11.2.

11.4. AIR-LIFT PUMPING

Water can be pumped from a well by releasing compressed air into a discharge pipe (air line) lowered into the well. Air bubbles mix with the water and reduce the specific gravity of the water column sufficiently to lift it to the surface. Because air-lift pumping is inefficient in comparison with other pumping methods, and because of the rather cumbersome and expensive equipment required, this method of pumping is rarely used as a permanent pumping system. In those instances where it is used, there is likely to be some special reason,
such as the need for aeration to remove an objectionable gas, or the occurrence of a highly corrosive or abrasive water that is destructive to pump parts. Air-lift pumping is used to a lesser extent in the preliminary testing and development of wells.

![Graph showing centrifugal versus reciprocating pump pressure and capacity characteristics](image)

**Figure 11.2. Centrifugal versus reciprocating pump pressure and capacity characteristics. (F. E. Myers Company, 1965)**

11.5. PUMP SELECTION

Basic pump design, anticipated pumping conditions, and specific installation procedures are factors that must be considered in choosing a pump for a water well. Pump engineers must outline the general opening conditions for the pump before a specific type is selected. Design parameters include:

1. Well diameter
2. Desired yield
3. Total dynamic head
   a. Pumping water level (shallow- or deep-well conditions)
   b. Above-ground head
   c. All friction losses in column, pipe, fittings, etc.
4. Horsepower requirements
   a. Brake horsepower
   b. Horsepower required to offset shaft losses (vertical turbine)
   c. Motor efficiency without thrust load
   d. Losses caused by friction in the thrust bearing
   e. Horsepower curve for varied discharge rates
5. Power source
   a. rpm preferred or required
6. Pumping deviation - system-head-curve parameters
7. Sand-pumping potential
8. NPSH and specific speed, if required
9. Water quality
10. Short- and long-term costs
   a. Initial capital costs
   b. Amortization of investment
   c. Power costs
   d. Supervision and maintenance
   e. Cost of downtime and standby equipment

After the most suitable type of pump has been determined from the available data, a specific pump is selected that will best fit pumping requirements at the site.

11.6. PITLESS ADAPTORS

A sanitary underground discharge assembly, called a pitless adaptor, provides the most practical solution to the sanitary completion of the upper part of a well when offset-pump installations are specified. This device, illustrated in Figures 11.3a and 11.3b, attaches directly to the well casing and extends the casing above the ground surface. It provides a watertight subsurface connection for buried pump discharge or suction lines. These pipes must be buried below the frost line to prevent freezing.

Until the development of the pitless adaptor, installing pumps in pits below ground level was common where frost protection for piping was required. Pump pits are always unsanitary, and the pitless adaptor provides a practical means of eliminating them.

Besides their application in offset-pumping installations, pitless adaptors are equally useful where the pump is installed in the well with the power drive mounted either on the well casing or in the well (centrifugal and submersible pumps). The pump may be removed from the well and replaced without disturbing the underground discharge pipe. A removable device sealed inside the adaptor directs the water into the permanently connected suction or pressure line. This device is suspended from the top of some pitless adaptors and may be lifted out vertically, giving full-diameter access to the well for repair or cleaning.
CHAPTER 12.

GROUNDWATER MONITORING TECHNIQUES

Approximately half the population of the United States is dependent upon groundwater for its drinking water supplies. There is growing evidence that this resource, once considered relatively pollution free, is being contaminated locally by municipal and industrial wastes. Groundwater contamination occurs when soluble or insoluble substances are introduced into the hydrogeologic environment as a result of man's activities. Groundwater pollution results when the level of the contaminant concentration restricts the potential use of groundwater. Groundwater contamination is so severe in certain localities that continued use of the water could lead to serious health problems. Even though serious groundwater pollution problems exist over rather small geographic areas, they often occur in areas having high population densities. Irresponsible and ignorant waste-disposal practices of the past will continue to affect groundwater quality for many years in spite of major detection and restoration efforts now being pursued.

This chapter focuses on where and why groundwater contamination occurs, the methods used to locate contaminant plumes, the design and construction of wells to monitor groundwater quality, and the procedures used to clean up contaminated aquifers. Other aspects of monitoring such as sampling procedures, equipment used to obtain samples from wells, and procedures to assure quality of the samples are discussed only briefly because most of these activities are performed by environmental consultants, not well contractors.
Why has groundwater contamination occurred? In the past, people believed that nature provided much better protection for groundwater quality than it actually does. Instances of groundwater pollution such as the Love Canal near Niagara Falls, New York have caused immediate and widespread concern for protection of the underground environment and a realization that chemical contamination of this environment is both serious and widespread (EOS, 1981). In St. Louis Park, Minnesota, for example, creosote contamination of soil and underlying aquifers over a 50-year period has caused the closing of nearby municipal wells. High concentrations of phenols, a potential carcinogen, have been found in these wells. In another example, 100 water wells surrounding a landfill in Jackson Township, New Jersey were closed because of organic chemical pollution (U.S. Environmental Protection Agency, 1980a). Although the landfill, which was constructed in a porous sand but never sealed properly, was only licensed to accept sewage sludge and septic tank wastes, chemical analyses of the groundwater in the vicinity of the landfill indicate high concentrations of chloroform, benzene, methylene, chloride, trichloroethylene, ethylbenzene, and acetone. Serious health problems have been reported by the well owners. On an even larger scale, 30 mi² of the shallow aquifer underlying the Rocky Mountain Arsenal near Denver, Colorado have become contaminated by chemical byproducts resulting from the manufacture of pesticides.

In the United States alone, over 250,000 new chemicals are created each year. Of these, some of the most troublesome are the widely used synthetic organic chemicals which are often carcinogenic or toxic to man. Over a million organic chemicals already exist, and several thousand new ones are developed each year. Sources of organic chemicals in groundwater are leaking industrial lagoons, septic tanks, leaking gasoline storage tanks, agricultural chemicals, and residues from paints and solvents.

After certain organic chemicals have entered an aquifer because of inadequate disposal practices, Bushing of the aquifer or natural dilution of contaminants is so slow that total cleansing of the aquifer may not occur except over extremely long periods of time—hundreds or even thousands of years. Other organic chemicals have high mobility in the subsurface environment and, once the source is cut off, the water quality returns to normal within 10 to 20 years. The fate of organic compounds in groundwater and their rate of movement through the system depends in part on their sorptive capacity, volatility, dilution, biological activity, and chemical reactions.

Until recently, few people realized the extent of underground contamination or its adverse impact on groundwater quality. Because groundwater contamination is usually difficult to contain or control, governmental policies have been directed at its early detection, treatment, and subsequent elimination. These policies are being expanded to eliminate waste disposal practices that lead to subsurface contamination.

The water well industry must become involved in the successful detection and elimination of threats to groundwater quality. Every drilling contractor should be aware of potential threats to groundwater quality from abandoned wells, leaky sanitary landfills, poorly functioning sewage treatment facilities, and industrial or municipal wastewater ponds.

12.1. MAJOR FEDERAL LEGISLATION PERTAINING TO GROUNDWATER QUALITY AND MONITORING PROCEDURES
Several federal laws and much recent state legislation have established groundwater monitoring requirements for various potential contaminant sources. Some states that have assumed the responsibility (primacy) for implementing federal laws may impose more rigorous requirements than the federal law mandates. Thus, contractors installing monitoring wells should ascertain which regulations must be followed in their state.

No single federal law deals specifically with the problem of groundwater contamination. Various laws that affect groundwater were drafted to help solve specific environmental problems. The first major federal law that recognized the importance of groundwater was the Safe Drinking Water Act of 1974 (SDWA, PL 93-523), which established standards for insuring the safety of drinking water. Part of this law, the Underground Injection Control (IJIC) program, regulates injection wells to prevent contamination of groundwater used for drinking water. Wells injecting wastes into the ground must be monitored to insure that wastes are contained in the prescribed zone. Another aspect of this law protects sole-source aquifers for drinking water. A sole-source aquifer is the dominant or only aquifer in a region.

The Resource Conservation and Recovery Act of 1976 (RCRA, PL 94-80) establishes guidelines for managing solid and hazardous wastes. This is the major federal law relating to groundwater monitoring. The primary objectives of monitoring under this act are to (1) detect whether a facility is discharging hazardous wastes to the highest aquifer, (2) determine whether the concentrations of specific hazardous waste constituents are within prescribed limits, and (3) measure the effectiveness of corrective measures taken at the site. The Toxic Substance Control Act of 1983 (TSCA, PL 94-469) also recognized the significance of groundwater quality protection.

Groundwater monitoring activities are also mandated under the Surface Mining Control and Reclamation Act of 1977 (SMCRA, PL 95-87). This law specifies that pre-mining baseline groundwater data be obtained, as well as data during mining activities and after closure of the facility.

One other law, the Comprehensive Environmental Response, Compensation, and Liability Act of 1983 (CERCLA, PL 96-510), was created to facilitate clean-up problems at waste sites that resulted from accidents in transporting hazardous wastes and at waste sites where ownership could not be determined. This act set up a trust fund (Superfund) to finance the cleanup of spills and the reclamation of closed sites. Although specific groundwater monitoring requirements are not prescribed in this law, it is likely that requirements developed under this law will eventually follow those given in the Resource Conservation and Recovery Act.

### 12.2. GROUNDWATER CONTAMINATION SOURCES

The major threats to groundwater quality from all contaminant sources are (1) septic tank systems, (2) sanitary landfills, (3) chemical landfills, and (4) wastewater disposal ponds. The presence of any of these sources can have a pronounced impact on groundwater quality (Table 12.1). The total number of active hazardous and nonhazardous industrial and municipal waste sites is estimated at 141,000 (U.S. Environmental Protection Agency, 1980b). Furthermore, there may be more than 150,000 inactive sites that may be potential threats to groundwater quality. The U.S. Environmental Protection Agency (EPA, 1980b) has indicated that, of the 32,000 to 50,000 disposal sites that may contain hazardous waste, 1,200...
to 2,000 could pose serious health or environmental problems. Until recently, about 80 percent of hazardous wastes were being disposed of improperly in landfills or lagoons and they will present a long-term threat to groundwater quality.

![Image of waste disposal sources](image)

<table>
<thead>
<tr>
<th>Waste Disposal Sources</th>
<th>Nondisposal Sources</th>
<th>Depletion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfills, dumps, and surface impoundments</td>
<td>Abandoned wells</td>
<td>Increased salinity</td>
</tr>
<tr>
<td>Mining wastes</td>
<td>Accidental spills</td>
<td>Salt-water encroachment</td>
</tr>
<tr>
<td>On-lot wastewater disposal systems</td>
<td>Agricultural chemical practices</td>
<td></td>
</tr>
<tr>
<td>Radioactive wastes</td>
<td>Artificial recharge</td>
<td></td>
</tr>
<tr>
<td>Sludge management via land spreading</td>
<td>Highway deicing compounds</td>
<td></td>
</tr>
<tr>
<td>Injection wells</td>
<td>Petroleum exploration</td>
<td></td>
</tr>
<tr>
<td>Abandoned sites</td>
<td>Underground storage tanks and pipelines</td>
<td></td>
</tr>
</tbody>
</table>

*Table 12.1. Major Sources of Groundwater Pollution (After Canter, 1981)*

Another U.S. EPA report, The Surface Impoundment Assessment, suggests that 181,000 impoundments exist at 25,800 industrial sites. A study of 8,200 of the industrial sites shows that (U.S. EPA, 1980b):

1. 70 percent of the impoundments are unlined and possibly allow contaminants to enter the ground.

2. 10 percent of the sites that are unlined overlie usable aquifers and are on permeable soils. One-third are within 1 mi of a water supply well.

3. About 35 percent hold liquid wastes that may contain hazardous constituents.

4. As of 1980, only 5 percent of the sites were known to be monitored.

The degree of the contamination threat to groundwater supplies from landfills and wastewater ponds depends on several factors: toxicity and volume of the contaminant generated at each site, the nature of the geologic medium underlying the site, and the hydrologic conditions dominant in the area.

The recent discovery that many volatile organic chemicals are emanating from landfills and industrial disposal ponds is disturbing because they are known or suspected carcinogens and are not removed easily by natural geochemical processes in the ground. Many of these organic chemicals were found in a high percentage of wells recently tested by the U.S.
Environmental Protection Agency. The chemicals listed in Table 12.2 occur in groundwater in many industrial areas and in groundwater adjacent to municipal landfills.

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trichloroethylene</td>
<td>A high-volume industrial chemical used extensively as a solvent for degreasing metal and as a septic tank cleaner.</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>Used as a cleaning solvent, pesticide, and intermediate in the production of chlorofluoromethanes.</td>
</tr>
<tr>
<td>Tetrachloroethylene</td>
<td>A solvent that is widely used in dry-cleaning and degreasing operations.</td>
</tr>
<tr>
<td>1,1,1 Trichloroethane</td>
<td>Also known as methyl chloroform. It is used as an industrial cleaner and degreaser of metals, resin adhesive, and vapor-pressure depressant.</td>
</tr>
<tr>
<td>1,2 Dichloroethane</td>
<td>Used primarily as a raw material for the production of vinyl chloride. Every gallon of leaded gasoline produced in the United States contains dichloroethane as a lead scavenger. This chemical is also used as a paint solvent, cleaning solvent, and grain fumigant.</td>
</tr>
<tr>
<td>1,1-Dichloroethane</td>
<td>Imported for use as a solvent and cleaning agent in specialized processes.</td>
</tr>
<tr>
<td>Dichloroethylenes</td>
<td>A group of 3 isomers*. Cis 1,2-dichloroethylene and Trans 1,2-dichloroethylenes have not had wide industrial usage; 1,1-dichloroethane is used as a chemical intermediate in the production of methyl chloroform.</td>
</tr>
<tr>
<td>Methylene chloride</td>
<td>Used in the manufacture of paint and varnish removers, insecticides, solvents, pressurized spray products, and Christmas tree bubble lights.</td>
</tr>
<tr>
<td>Vinyl chloride</td>
<td>Used for over 40 years in producing polyvinyl chloride, which is the most widely used material for the production of plastics.</td>
</tr>
</tbody>
</table>

*Isomers are two or more chemical compounds, radicals, or ions containing the same numbers of atoms of the same elements in the molecule, radical, or ion, and hence having the same molecular formula but differing in the structural arrangement of the atoms and consequently in one or more properties.

Table 12.2. Typical Synthetic Organic Chemicals and Their Major Industrial Uses (U. S. Environmental Protection Agency, 1980c; Canter, 1981)

Other less obvious threats to groundwater quality come from a variety of sources. For example, abandoned wells can be a severe problem if poor-quality water enters aquifers having good-quality water via uncemented well bores. This problem is especially serious in agricultural areas, where animal wastes, pesticides, and herbicides can easily enter the groundwater system through open well bores. In many coastal communities in Florida and California, salt-water encroachment caused by overpumping of fresh-water supplies is a major problem. In the North, heavy and often indiscriminate applications of road deicing
salts, and poorly constructed (uncovered) storage areas, can lead to high chloride concentrations in underlying aquifers.

Leaking gasoline storage tanks at automotive service centers, most of which have been installed in the last 35 years, are a serious local problem in an increasing number of communities. This type of pollution is especially detrimental because drinking water becomes unpalatable when it contains extremely low concentrations of petroleum products (Clean Environment Commission, 1976).

Another example is the broad range of pesticides being applied to farmland. This nonpoint source of potential contamination is extremely difficult to control. Any type of injection well can also create a water-quality problem if some of the wastes reach an aquifer containing good-quality water. Especially serious are radioactive wastes. These substances are extremely dangerous to humans for anywhere from 30 to 500,000 years. Yet, while the volume of these wastes has risen dramatically, no safe disposal sites have been identified or built. Early attempts to bury radioactive wastes have been largely unsuccessful because the wastes could not be prevented from contaminating groundwater supplies. Most nuclear-power generators are now storing their wastes aboveground at plant sites until safe sites can be identified.

Efforts to control contamination problems by regulation have been initiated by federal, state, and local governments. Common methods of control include:

1. Reducing the volume of material to be discarded by compaction, incineration, or other pretreatment schemes.
2. Selection of disposal sites that utilize the natural ability of the underground environment to remove contaminants, thereby preserving groundwater quality.

3. Improving engineering aspects of disposal sites, such as the addition of leachate collection systems, installation of double clay liners, or the use of synthetic liners.

### 12.3. EFFECT OF AQUIFER CHARACTERISTICS ON THE SPREAD OF GROUNDWATER CONTAMINATION

In the past, the least expensive and most widely used waste management option for both municipal and industrial wastes has been the sanitary landfill, where wastes are compacted and covered with earth. In any geographic area other than arid zones, the fill is subjected to percolating rainwater or snowmelt which eventually flows out the bottom of the landfill site and moves into the local groundwater system. These percolated waters, known as leachates, can contain large amounts of inorganic and organic contaminants. At some sites, the leachate is collected and treated. But even in the best engineered sites, some leachate escapes into the groundwater system because no permanent engineering solution has been found to isolate the leachate completely from the groundwater.

Common inorganic constituents found in leachates from sanitary landfills are listed in Table 12.3. The concentration of inorganic materials in leachates can be compared with the typical

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Representative Range (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium (K⁺)</td>
<td>200 - 1,000</td>
</tr>
<tr>
<td>Sodium (Na⁺)</td>
<td>200 - 1,200</td>
</tr>
<tr>
<td>Calcium (Ca²⁺)</td>
<td>100 - 3,000</td>
</tr>
<tr>
<td>Magnesium (Mg²⁺)</td>
<td>100 - 1,500</td>
</tr>
<tr>
<td>Chloride (Cl⁻)</td>
<td>300 - 3,000</td>
</tr>
<tr>
<td>Sulfate (SO₄²⁻)</td>
<td>10 - 1,000</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>500 - 10,000</td>
</tr>
<tr>
<td>Iron (Fe) (total)</td>
<td>1 - 1,000</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>0.01 - 100</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>0.01 - 1</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>0.1 - 100</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>Nitrate (NO₃⁻)</td>
<td>0.1 - 10</td>
</tr>
<tr>
<td>Ammonia (NH₃⁺)</td>
<td>10 - 1,000</td>
</tr>
<tr>
<td>Phosphorus (P) as phosphate (PO₄³⁻)</td>
<td>1 - 1,000</td>
</tr>
<tr>
<td>Organic nitrogen</td>
<td>10 - 1,000</td>
</tr>
<tr>
<td>Total dissolved</td>
<td></td>
</tr>
<tr>
<td>organic carbon</td>
<td>200 - 30,000</td>
</tr>
<tr>
<td>COD (chemical oxidation demand)</td>
<td>1,000 - 90,000</td>
</tr>
<tr>
<td>Total dissolved solids</td>
<td>5,000 - 40,000</td>
</tr>
<tr>
<td>pH</td>
<td>4 - 8</td>
</tr>
</tbody>
</table>

*(Leckie et al., 1975; Griffin et al., 1976)*

**Table 12.3. Representative Ranges for Various Inorganic Constituents in Leachate from Sanitary Landfills**
inorganic levels found in groundwater existing in various rock media to determine the leaching effect of water percolating through a waste site (Table 12.4). It is not known how long leachates continue to contaminate aquifers underlying landfills, but some landfills from the Roman Empire are still producing leachate (Freeze and Cherry, 1979). Contamination plumes can spread thousands of feet down gradient from a source, and once in the ground, they may remain there for many years even if the contaminant source is removed.

The hydrogeologic setting plays a role in determining the degree to which a landfill can alter water quality in local aquifer systems. The type of soils and their ability to adsorb contaminants, how far the landfill is situated above the water table or confined aquifer,

![Table 12.4. Typical Chemical Analyses of Groundwater taken from Different Rock Types (mg/ltr)](image-url)
and the hydraulic properties of the aquifer contribute to or reduce contaminant concentrations. Two typical geologic settings are presented in Figures 12.1 and 12.2 that demonstrate the interaction between the landfill leachates and the local hydrogeology. These illustrations are instructive in showing the potential flow paths taken by contaminants.

Drilling contractors and engineers should become familiar with potential contaminant flow paws in any waste project area because regulations require that most monitoring wells be placed downgradient Cam the contaminant source. Initially, an estimate of the dimensions of the plume must be made on the basis of assumed hydraulic conductivity, porosity, and dispersion values for the aquifer. Any boundary conditions such as faults or changes in rock type must also be considered. It is important to recognize that some contaminants will
become soluble in water, whereas others such as hydrocarbons will float on the surface of the groundwater. The density of a soluble contaminant relative to that of water will affect its penetration into the aquifer.

In the discussion below, flow of the contaminant through the vadose zone will not be considered, but the reader should be aware that many forms of instrumentation, mainly lysimeters and various types of electrical and nuclear sensors, can be used to monitor this zone.

Once in the aquifer, the primary driving force for contaminant movement is created by the hydraulic gradient that produces groundwater flow. Contaminants entering the groundwater system are thus carried downgradient, forming a contaminant plume. This type of contaminant movement is termed "advection." Other factors also influence the shape of the plume, including two types of hydrodynamic dispersion—mechanical mixing and molecular diffusion. These two processes cause a spreading (dispersion) of the contaminant over a much larger area than advection alone would produce, and, consequently, a dilution of the contaminant away from the source area. Mechanical mixing processes include velocity differences within the pore openings, velocity differences caused by differences in pore sizes through which the water molecules move, and the degree of tortuosity (length) of the pore channels.

Molecular diffusion (chemical dispersion) can also occur. In the absence of any groundwater movement, a slug of highly concentrated chemical will move outward from its origin toward points of lower concentration. This type of dispersion occurs because of the kinetic activity of the ionic or molecular constituents. The effect of molecular diffusion on contaminant dispersion is usually much less than the effect of mechanical mixing processes, and except in the case of no groundwater movement at all (an improbability), it can probably be ignored in most instances in estimating the spread of contaminant plumes. An exception occurs with light organic chemicals which have moved upgradient in some cases.
It is possible to project how a contaminant plume actually spreads by advection and mechanical mixing. Figure 12.3a shows the theoretical downgradient movement of a plume from a continuous contamination source. Note the marked dispersion of the contaminant as it moves downgradient. Depending on the exact nature of the aquifer, the dispersion may be of even greater magnitude than the longitudinal movement (advection) shown in Figure 12.3a. In Figure 12.3b, a contaminant is injected periodically into the aquifer. Mechanical mixing coupled with advective flow creates the ellipsoid-shaped plumes. Clearly, the larger the total area covered by the plume, the more diluted the contaminant becomes.

The density of the contaminant plays a part in determining the vertical dimensions of the plume. If a material entering an aquifer is heavier than water, it sinks slowly as it disperses transversely and longitudinally. The density of the material in relation to water, as well as the hydraulic nature of the aquifer, will govern the vertical penetration of the plume as it moves downgradient (Figure 12.4).

Many chemical and biochemical reactions can take place in the subsurface environment to either augment or, more likely, reduce the concentration of a contaminant. The most
important of these are solution-precipitation, oxidation-reduction, adsorption-desorption, acid-base reactions, and microbial cell synthesis. Some of these reactions may take place in the unsaturated zone before the contaminant reaches the aquifer. Once in the aquifer, different contaminants in the same plume may travel at different velocities depending on how they react with the geologic medium. Any investigation of groundwater contamination should include an analysis of the chemical or biological reactions taking place and the effect of these reactions on the strength of the contaminant plume.

In summation, many factors play a part in the spreading and concentration rate of a contaminant: anisotropic/isotropic properties of the rock medium, advection rate, hydrodynamic dispersion processes, and reaction potential with the subsurface materials. Therefore, underground movement of groundwater contaminants is often exceedingly difficult to analyze in a straightforward manner. Many sophisticated methods are now being used to determine contaminant movement, including special mathematical modeling techniques, electrical (surface resistivity) methods, radioactive tracers, various dyes and salts, water temperature, and baker's yeast. Some of these techniques are discussed later in this chapter.

12.4. DELINEATING CONTAMINANT PLUMES

Openings in rocks or unconsolidated materials are not regularly spaced, and the permeability of the aquifer material varies both vertically and horizontally. Thus, the flow of contaminants is highly anisotropic (Figure 125). In spite of these difficulties, it is necessary to estimate flow direction within the aquifer so that the source of contamination and the direction of plume movement can be determined.

Figure 12.5. Comparison of the advance of contaminant zones influenced by hydrodynamic dispersion. (a) Perfectly homogeneous granular medium; (b) fingering caused by layered beds and lenses. (Freeze, R. Allan and Cherry, John A., GROUNDWATER, 1979. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ)

Usually, the general direction of groundwater flow can be established on the basis of the local topography (use of topographic maps or aerial photos) and the presence of streams or
rivers which act as groundwater discharge boundaries. Recall that near-surface groundwater flow will generally follow surface drainage patterns. If the flow direction cannot be established, three small-diameter wells are temporarily installed into the aquifer. An analysis of the relative water table or potentiometric surfaces in the wells will reveal the direction of flow. For anisotropic aquifers, however, the direction of flow may not be parallel to the hydraulic gradient.

To determine the dimensions of a plume, test borings can be made and water samples taken. Several borehole geophysical methods are used in defining the extent of plumes; the most important of these are resistivity, conductivity, neutron, hole caliper, and temperature. Resistivity and conductivity values of the groundwater are affected by the contaminating substance and thus are an indication of the plume's presence at a site. Gamma ray and other nuclear methods provide information on subsurface ethology, particularly zones that have high permeability. It can be expected that contaminant migration will be greatest in these zones. Hole calipers indicate the presence of solution channels penetrated by a borehole in hard terrains. Temperature logs are useful in tracing the movement of injected water in highly permeable zones and detecting any changes in flow rate over time.

12.5. MONITORING CONTAMINANT MOVEMENT (TRANSPORT)

In many instances of groundwater contamination, the ability to predict how the contaminant plume will behave in the future can only be done on the basis of expensive drilling and sampling programs. Many scientists interested in the movement of contaminants in the subsurface believe, however, that it will soon be possible to use mathematical modeling techniques to estimate the spread of a contaminant and its strength at any point in the plume. The steps or processes used to build the model are shown in Figure 12.6. Five basic steps are accomplished in sequence:

1. In the first step, the basic factors affecting contaminant transport are identified—hydraulic characteristics of the aquifer, the physical and chemical properties of the aquifer materials, and the chemical and physical properties of the contaminants entering the groundwater system.

2. The attenuating processes for single chemicals are established. Different chemicals will move at varying rates and therefore occur at different concentrations in the aquifer.

3. In the third step, a mathematical model is set up to account for the attenuation processes, and a method of solving the equation is determined.

4. Predictions are made on the basis of the answers obtained in Step 3 for the occurrence of the various contaminant in the aquifer at a particular time.

5. In the last step, the validity of the model is assessed by comparing the model's results to any known field data. If the results differ significantly, the various model inputs are adjusted to produce better correlation with the field data.
In this modeling process, the factors identified in Step 1 are the most difficult to determine. This is true because the construction of virtually all aquifers is highly complex, with little uniformity either vertically or horizontally. Thus, it is difficult to predict how fast the contaminants will move through the aquifer, at what depth, and over what area they will be dispersed within a certain time. Furthermore, the geochemical attenuation mechanisms for many chemicals are not thoroughly understood. For these reasons, some transport models have not yielded good results, and field data are much more reliable. Many groundwater scientists are working on ways to improve model accuracy, however, and, because the use of a model can be so much less costly than field work in estimating plume dimensions and contaminant concentrations, the use of contaminant transport models will probably increase significantly in the future.

Even though the mathematical analysis and the complex geochemical relationships that are a fundamental part of any contaminant transport model may be beyond the experience of most drilling contractors, much of this information will probably be available as "canned" models adaptable to a wide range of geologic situations. The contractor or consulting hydrogeologist will then be able to use the models to define a cost-effective field drilling program. Results from the field data can then be used to calibrate the model for the specific site.

12.6. LOCATING MONITORING WELLS

Once the areal extent of the plume has been defined, several monitoring wells are installed in or adjacent to the plume. The purpose of a monitoring well is to (Lewis, 1982):

1. Determine the hydrogeologic properties of the formation in which the contaminant exists.

2. Determine the water table or potentiometric surfaces of all aquifers in the system.

3. Permit access for the collection of water-quality samples for detection of contaminants

4. Monitor the movement of the contaminant plume.

Usually one well is sited near the center of the plume just downgradient from the contaminant source. Another well is installed downgradient of the contaminant source, outside the limits of the plume. For ambient environmental data, one well is placed
upgradient of the contaminant source. Other wells may be installed to verify the amount of
dispersion taking place. The most difficult decision is rarely where to place the monitoring
wells, but at what depths should the samples be taken. Selection of the most appropriate
depths will depend on the density of the contaminant, the anisotropic characteristics of the
aquifer, and the slope of the water table or potentiometric surface. The design of the
monitoring network is extremely important if maximum information concerning the extent of
the contamination is to be obtained.

In the past, too few monitoring wells were required for each disposal site. Thus it was not
possible to adequately monitor contaminant movement. In practice, the number of wells
required to adequately monitor a specific disposal site will vary greatly, depending on the
local hydrogeology. If the disposal site is higher than the surrounding landscape, for
example, leachates may flow some distance in all four directions. In this instance, at least
four wells would be needed, plus one other to monitor the upgradient chemistry. Ideally,
some wells would be installed at more than one depth in the aquifer to verify if vertical flow
is occurring or if the spread of the contaminant varies at different depths. Proper placement
of monitoring wells must be based on accurate information concerning the groundwater flow
direction at the waste disposal site and the type of contaminant.

Although monitoring wells can be drilled by virtually any drilling method, some methods
may be more suitable in certain situations. Table 12.5 lists the major methods used to install
monitoring wells, and their advantages and disadvantages.

For monitoring work, many of the objectives of a drilling program are similar to those for a
water well, but some of the steps must be done with greater care to insure that the water
quality is protected and reliable water samples can be obtained. Specific steps in monitoring
well construction include:

1. Ability to penetrate all formation materials at a reasonable rate and to construct a borehole
diameter of the proper size, assuring that cross-contamination will not occur.

2. Ability to provide accurate information on all the formations being drilled.

3. Containment of cuttings and drilling fluids so they do not contaminate the formation.

4. Collection of water samples at various depths during drilling.

5. Ability to accommodate for lost-circulation problems, confining pressures, and flammable
and toxic substances.

6. Construction of the monitoring well either during the drilling process or immediately
thereafter.

7. Ability to maintain an open borehole long enough for geophysical exploration (if required)
and data analysis.
<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Hollow-stem auger    | • No drilling fluid is used, eliminating contamination by drilling fluid additives  
                        • Formation waters can be sampled during drilling by using a screened auger or advancing a well point ahead of the augers  
                        • Formation samples taken by split-spoon or core-barrel methods are highly accurate  
                        • Natural gamma-ray logging can be done inside the augers  
                        • Hole caving can be overcome by setting the screen and casing before the augers are removed  
                        • Fast  
                        • Rigs are highly mobile and can reach most drilling sites  
                        • Usually less expensive than rotary or cable tool drilling  | • Can be used only in unconsolidated materials  
                        • Limited to depths of 100 to 150 ft (30.5 to 45.7 m)  
                        • Possible problems in controlling heaving sands  
                        • May not be able to run a complete suite of geophysical logs |
| Direct rotary        | • Can be used in both unconsolidated and consolidated formations  
                        • Capable of drilling to any depth  
                        • Core samples can be collected  
                        • A complete suite of geophysical logs can be obtained in the open hole  
                        • Casing is not required during drilling  
                        • Many options for well construction  
                        • Fast  
                        • Smaller rigs can reach most drilling sites  
                        • Relatively inexpensive  | • Drilling fluid is required and contaminants are circulated with the fluid  
                        • Drilling fluid mixes with the formation water and invades the formation and is sometimes difficult to remove  
                        • Bentonitic fluids may absorb metals and may interfere with other parameters  
                        • Organic fluids may interfere with bacterial analyses and/or organic-related parameters  
                        • During drilling, no information can be obtained on the location of the water table and only limited information on water-producing zones  
                        • Formation samples may not be accurate  
                        • Casing is required to keep the hole open when drilling in soft, caving formations below the water table  
                        • When more than one water-bearing zone is encountered and hydrostatic pressures are different, flow between zones occurs during the time drilling is being completed and before the borehole can be cased and grouted properly  
                        • Relatively more expensive than other methods  
                        • May not be economical for small jobs |
| Air rotary           | • No water-based drilling fluid is used, eliminating contamination by additives  
                        • Can be used in both unconsolidated and consolidated formations  
                        • Capable of drilling to any depth  
                        • Formation sampling is excellent in hard, dry formations  
                        • Formation water blown out of the hole makes it possible to determine when the first water-bearing zone is encountered  
                        • Field analysis of water blown from the hole can provide information regarding changes for some basic water-quality parameters such as chlorides  
                        • Fast  |  |
| Cable tool           | • Only small amounts of drilling fluid are required (generally water with no additives)  
                        • Can be used in both unconsolidated and consolidated formations; well suited for extremely permeable formations  
                        • Can drill to depths required for most monitoring wells  
                        • Highly representative formation samples can be obtained by an experienced driller  
                        • Changes in water level can be observed  
                        • Relative permeabilities for different zones can be determined by skilled drillers  
                        • A good seal between casing and formation is virtually assured if flush-jointed casing is used  
                        • Rigs can reach most drilling sites  
                        • Relatively inexpensive  | • Minimum casing size is 4 in (102 mm)  
                        • Steel casing must be used  
                        • Cannot run a complete suite of geophysical logs  
                        • Usually a screen must be set before a water sample can be taken  
                        • Slow |

Table 12.5. Drilling Methods for Monitoring Wells
12.7. PERSONNEL SAFETY AT MONITORING SITES

Safety should be a primary concern of water well contractors engaged in drilling and constructing monitoring wells. Besides the usual physical herds of normal drilling activities, chemical, biological, radiological, and explosive hazards are added when drilling monitoring wells. So many toxic chemicals have been placed in the ground, either accidentally or intentionally, that drillers must use extreme caution when drilling in areas of known or suspected waste sites. In the past, many extremely toxic chemicals were mixed indiscriminately into ordinary municipal waste streams. Even the innocent disposal by homeowners of many dangerous organic chemicals has led to their introduction into the groundwater system beneath sanitary landfills. Unfortunately, the exact location or the extent of many former waste disposal sites are not known with precision. Furthermore, many chemicals may appear to be harmless and any injury may be rather insignificant on a short-term basis. Yet long-term effects may be acute, causing premature death, unusual forms of cancer, or generally poor health.

Some of the most significant dangers are:

1. Explosions from methane gas produced by the decay of organic materials in sanitary landfills. An explosion potential also exists in monitoring work involving hydrocarbon recovery.

2. Toxic substances used in manufacturing pesticides, herbicides, solvents, paints, and other common products. Sometimes certain nontoxic chemicals placed in a disposal site will react with other chemicals to produce highly toxic chemicals.

3. Biologic wastes from hospitals or medical laboratories at universities that contain bacteria and viruses.

4. Chemical wastes that are corrosive, highly reactive, flammable, or explosive.

5. Vapors from any type of waste.

6. Radioactive wastes from hospitals and industrial and university laboratories.

One vital fact must always be kept in mind—the combination of substances at a waste site may have a more powerfully adverse effect on human health than they would individually. Before attempting to conduct monitoring work at a waste site, the drilling contractor should learn exactly what types of wastes were buried there, provide the necessary protective clothing and training for personnel, and stress that any physical changes in a worker's health may be caused by contact with the waste. Always be prepared for "worst case" conditions.

Any form of drilling is relatively dirty in the sense that it is difficult to avoid contact with cuttings, water encountered in the borehole, and surficial residues at the site. The following practices must be followed at any known or suspected hazardous waste site. (Maslansky, 1983)
1. "Personnel should wear properly selected and fitted protective clothing and respirators at all times. Personnel must be given suitable training in the use, limitations, maintenance, cleaning, and storage of protective clothing and equipment."

2. "Personnel should not eat, drink, chew gum or tobacco, smoke, take medicines, or perform any other practice that might increase hand-to-mouth transfer of toxic materials from gloves, unwashed hands, or equipment."

3. "Personnel should not have excessive facial hair (heavy mustaches, beards) which can prevent the proper fit of respirators."

4. "Personnel should avoid unnecessary contact with hazardous materials by staying clear of puddles, vapors, mud, discolored surfaces, and containers or site debris."

Carelessness during routine daily activities at the site can lead to serious personal contamination or to contamination of others. Several important habits should be practiced:

1. Always wash hands before using rest room.

2. Leave the site for lunch, removing all protective (contaminated) clothing, and wash thoroughly.

3. Wash hands after handling contaminated equipment.

4. Do not take contaminated clothing home to launder.

5. Wear the required protective clothing at all times, even if the need is not apparent. Demand that it be fitted properly. Even a short exposure to a toxic substance can be deadly.

6. Because protective clothing is cumbersome to wear and is often uncomfortable in hot weather, take appropriate rest periods to avoid accidents caused by fatigue or physical irritation.

Even if every safety precaution is taken, an emergency may develop at any time when doing monitoring work. Emergency plans should be well established and understood by everyone involved in the project. First aid equipment should be available, the routes to emergency care centers known, and the necessary personal contacts established at the care centers. All steps of the standard emergency procedures should be practiced so that any team member can take charge.
**12.8 DESIGN OF MONITORING WELLS**

Figure 12.7 shows typical observation well, piezometer, and lysimeter construction schemes.

The particular design of a monitoring well will depend on (l) how the well is to be used—whether for taking water samples for measuring the elevation of the water table or potentiometric surface, or for recovering contaminants, (2) the hydrogeologic environment, (3) the chemical nature of the contaminants, and (4) whether the well bore will be used to conduct geophysical investigations. The design consultant should keep in mind that the cost of the best engineered monitoring well constructed of the most suitable materials will be only a fraction of the long-term costs for water quality analysis. Therefore, the most suitable well materials and construction practices should be selected for monitoring wells.

Many monitoring wells are constructed of 2-in casing and screen, although a large number are 4, 6, or 8 inches in diameter. The most appropriate diameter will depend on numerous site-specific factors. For shallow monitoring wells or those used for measuring water level and routine sampling 2-in well screens and casing may be suitable. For better development, deeper wells, or where some form of pumping test or borehole geophysical investigation is necessary, the screen and casing may need to be 4 inches in diameter. Taking representative samples from Tin wells is more difficult than for 2-in wells because many pumps manufactured for sampling 2-in monitoring wells are technically superior to larger pumps in that they preserve the true chemical character of the sample. They can be pumped at only extremely low rates, however, making their use impractical in wells 4 inches in diameter or larger. If 2-in screens are installed in dirty or tight formations, the driller cannot develop the well properly. Water samples taken from poorly developed wells may not be chemically representative of the water in the formation because recharge to the well is so slow that the person who takes the sample cannot spend the time needed to collect a representative sample.

**12.8.1. Screen Criteria for Monitoring Wells**
Well screens used for monitoring work should have the following characteristics:

1. Screens should be constructed from a material that is inert in the water being tested.

2. Open area should be maximized to facilitate rapid sample recovery.

3. Slot sizes should retain filter pack or natural formation consistent with the capability to develop the welt

4. Slot openings should be nonplugging in design.

5. Slot openings, slot design, open area, and screen diameter should permit effective development.

Selection of the screen material must be done with care because many common screen or casing materials such as PVC, low-carbon steel, and even stainless steel may react with the groundwater, producing erroneous water quality data. In general, the following factors should be considered when selecting screen and casing materials:

1. Contaminants to be sampled
2. Chemical reactivity/inertness
3. Strength of material
4. Ease of installation
5. Cost of material

Table 12.6 lists the major types of materials used for monitoring wells, along with recommendations for their use. Teflon (Teflon is a registered trademark of E.I. DuPont DeNemours and Co., Inc.) is the most inert material currency being used, but its cost may make its use inappropriate in groundwater environments where less costly materials are satisfactory. PVC materials are suitable for monitoring most landfills unless organic chemicals are present in the groundwater. If they are present, stainless steel or Teflon materials must be used. Relatively inert metals such as 304 or 316 stainless steel are not suitable for groundwater in which heavy metals are present, because leaching of chromium or other metallic components may occur. Selection of the screen and casing material generally depends upon the chemical manure of the groundwater, not cost of the screen or casing material. The laboratory doing the analytical chemistry of the water samples should be informed of all materials used in the well.
<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC (Polyvinylchloride)</td>
<td>• Lightweight</td>
<td>• Weaker, less rigid, and more temperature sensitive than metallic materials</td>
</tr>
<tr>
<td></td>
<td>• Excellent chemical resistance to weak alcohols, alcohols, aliphatic hydrocarbons, and oils</td>
<td>• May adsorb some constituents from groundwater</td>
</tr>
<tr>
<td></td>
<td>• Good chemical resistance to strong mineral acids, concentrated oxidizing acids, and strong alcohols</td>
<td>• May react with and leach some constituents from groundwater</td>
</tr>
<tr>
<td></td>
<td>• Readily available</td>
<td>• Poor chemical resistance to ketones, esters, and aromatic hydrocarbons</td>
</tr>
<tr>
<td></td>
<td>• Low priced compared to stainless steel and Teflon</td>
<td></td>
</tr>
<tr>
<td>Polypropylene</td>
<td>• Lightweight</td>
<td>• Weaker, less rigid, and more temperature sensitive than metallic materials</td>
</tr>
<tr>
<td></td>
<td>• Excellent chemical resistance to mineral acids</td>
<td>• May react with and leach some constituents into groundwater</td>
</tr>
<tr>
<td></td>
<td>• Good to excellent chemical resistance to alcohols, ketones, and esters</td>
<td>• Poor machinability — it cannot be slotted because it melts rather than cuts</td>
</tr>
<tr>
<td></td>
<td>• Good chemical resistance to oils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Fair chemical resistance to concentrated oxidizing acids, aliphatic hydrocarbons, and aromatic hydrocarbons</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Low priced compared to stainless steel and Teflon</td>
<td></td>
</tr>
<tr>
<td>Teflon</td>
<td>• Lightweight</td>
<td>• Tensile strength and wear resistance low compared to other engineering plastics</td>
</tr>
<tr>
<td></td>
<td>• High impact strength</td>
<td>• Expensive relative to other plastics and stainless steel</td>
</tr>
<tr>
<td></td>
<td>• Outstanding resistance to chemical attack; insoluble in all organics except a few exotic fluorinated solvents</td>
<td></td>
</tr>
<tr>
<td>Kynar</td>
<td>• Greater strength and water resistance than Teflon</td>
<td>• Not readily available</td>
</tr>
<tr>
<td></td>
<td>• Resistant to most chemicals and solvents</td>
<td>• Poor chemical resistance to ketones, esters, and aromatic hydrocarbons</td>
</tr>
<tr>
<td></td>
<td>• Lower priced than Teflon</td>
<td></td>
</tr>
<tr>
<td>Mild steel</td>
<td>• Strong, rigid; temperature sensitivity not a problem</td>
<td>• Heavier than plastics</td>
</tr>
<tr>
<td></td>
<td>• Readily available</td>
<td>• May react with and leach some constituents into groundwater</td>
</tr>
<tr>
<td></td>
<td>• Low priced relative to stainless steel and Teflon</td>
<td>• Not as chemically resistant as stainless steel</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>• High strength at a great range of temperatures</td>
<td>• Heavier than plastics</td>
</tr>
<tr>
<td></td>
<td>• Excellent resistance to corrosion and oxidation</td>
<td>• May corrode and leach some chromium in highly acidic waters</td>
</tr>
<tr>
<td></td>
<td>• Readily available</td>
<td>• May act as a catalyst in some organic reactions</td>
</tr>
<tr>
<td></td>
<td>• Moderate price for casing</td>
<td>• Screens are higher priced than plastic screens</td>
</tr>
</tbody>
</table>

**Table 12.6. Well Casing and Screen Materials**

Screens used for monitoring are almost always placed in materials having extremely low hydraulic conductivity. If possible, the open area of the screen should approximate the natural porosity of the formation, that is, 15 to 20 percent, so that the time required to take a representative sample is minimized. Because most sampling methods require that a water sample be taken only after 3 to 10 well-bore volumes have been removed, the amount of time dedicated to taking a single sample can be excessive if low-open area screens are installed.

Screen slot sizes must retain a high percentage of the filter pack or natural formation for all 2-in wells because effective development of these wells is particularly difficult. For larger diameter monitoring wells, the slot sizes can more nearly follow the recommendations for water wells. Development is most effective when the slot openings are distributed uniformly around the circumference of the screen so that as much of the formation and filter pack as possible can be reached by the development action. The configuration of the slot should permit all the development energy to reach the formation.
Slot openings should widen inward so that finer formation materials are pulled through the screen during development. Slots that are cut straight through the casing or those of the gauze type will tend to plug with fine material during development, thereby reducing significantly the open area of the screen. This is especially true for 2-in screens where any development that is done is relatively inefficient. Plugging of the slots increases the time needed to obtain a representative sample from the formation. For scientific purposes, water samples from monitoring wells are usually obtained from relatively thin zones in the aquifer. This can be accomplished by using multiple wells with short screen segments. Commonly, a nest of weds win be installed in single or multiple boreholes to gather water samples from several depths in the aquifer (Figure 12.8). Using this method, the vertical dimensions and contaminant strength of the plume can be determined.

Screens used for collecting water samples are typically 5 to 10 ft in length, because samples should come from specific depths and high yields are relatively unimportant. The well yield should be high enough, however, so that a reliable water sample can be collected quickly. Screens that monitor groundwater quality at the top of the water table are usually 10 to 20 ft in length, depending on the anticipated long-term changes in groundwater elevation. Some of the screen is always above the water table in the vadose zone. These screens are then used to monitor for the presence of hydrocarbons or other volatile substances that have reached the groundwater table.

12.8.2. Filter Pack Design
Monitoring wells are generally installed in formations having a wide range of particle sizes, which makes it difficult to filter pack effectively. Filter packing procedures recommended for water wells are not suitable for monitoring wells unless the hydraulic characteristics of the formation materials are similar to those of an aquifer. To exclude the entrance of fine silts, sands, and clays into a monitoring well, the grainsize distribution curve for the filter pack is selected by multiplying the Percent retained size of the finest formation sample by 2. This leads to a more conservatively sized filter pack than would be selected for a water well. Selection of too fine a pack will reduce the yield of the well, causing longer sampling times. Uniformity coefficients for filter pack material should range from 2 to 3. All pack material should be purchased from reputable suppliers who have properly cleaned and bagged the material. A sample of the cleaned filter pack should be collected and chemically analyzed in the event questions are raised regarding possible contamination from the pack. The design of a typical filter-packed monitoring well is shown in Figure 12.9.

12.8.3. Installation Procedures
All screens and casings used for monitoring wells should be in a sterile and contaminant-free condition when placed in the ground. Some manufacturers ship their products in this condition, but handling in the field requires a final wash with detergent or other solution. Table 12.7 lists typical decontamination solutions. Some form of steam cleaning, or high-pressure water-spraying technique combined with a low-sudsing soap or detergent, is recommended. In addition, acetone and hexane are used to clean drilling tools and sampling equipment at hazardous waste sites. Working components of the drilling rig (drill pipe, subs, collars, kelly, and all parts of the rig chassis near the borehole) should also be cleaned.

<table>
<thead>
<tr>
<th>Name of solution</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium bicarbonate</td>
<td>Effective for acids and bases, amphoteric, 5-15 percent</td>
</tr>
<tr>
<td></td>
<td>aqueous solution</td>
</tr>
<tr>
<td>Sodium carbonate</td>
<td>Effective for inorganic acids, good water softener, 10-20</td>
</tr>
<tr>
<td></td>
<td>percent aqueous solution</td>
</tr>
<tr>
<td>Trisodium phosphate</td>
<td>Good rinsing solution or detergent, 10 percent aqueous solution</td>
</tr>
<tr>
<td>Calcium hypochlorite</td>
<td>Excellent disinfectant, bleaching and oxidizing agent, 10</td>
</tr>
<tr>
<td></td>
<td>percent aqueous solution</td>
</tr>
</tbody>
</table>

Table 12.7. Decontamination Solutions (Richter and Collentine, 1983)

The method of joining screens to casing and of assembling the casing string must also be done so as to prevent contamination of the samples. In general, no solvent welds are recommended; all plastic screens and casing should be joined by threads and couplings or flush threads. The joints are made watertight by wrapping with Teflon tape or by placing a Teflon or Viton (Viton is a registered trademark of E.I. DuPont DeNemours and Co., Inc.) O-ring in the joint (Table 12.8).

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Plain square ends (no fittings to weld) | • Readily available in pipe and screen  
  • No need to purchase threads and couplings | • Special equipment and skills needed to field-weld metals  
  • Plastics are welded using solvent cement which causes the following problems:  
    — Cementing procedures are very temperature and moisture sensitive  
    — Cements must be cured after application  
    — Cements may interfere with groundwater quality analysis  
  Time spent welding may cause this type of fitting to actually cost more than threads |
| Threads and couplings       | • No solvents needed  
  • Lengths of pipe and screen joined quickly  
  • Readily available  
  • Reasonably priced | • May be difficult to get filler pack and/or grout past the lip of couplings  
  • May need to wrap threads with Teflon tape to make connections watertight |
| Flush threads               | • No solvents needed  
  • No couplings needed; filter packing and grouting simplified  
  • Lengths of pipe and screen joined quickly  
  • Readily available  
  • Reasonably priced | • May need to wrap threads with Teflon tape to make connections watertight  
  • Threads generally not compatible from manufacturer to manufacturer |

Table 12.8. Fitting Types
A primary objective of monitoring well construction is to make sure that contaminated groundwater does not enter contaminant-free geologic formations. Although some minor amount of cross-contamination may occur during drilling and well installation, the integrity of individual formations must be protected thereafter. This is usually accomplished by placing either bentonite or cement grout in the borehole above the filter pack in both single- and multiple-screen wells. Drill cuttings should not be placed in any open borehole annulus. To prevent downward migration of the bentonite or cement into the screen, the filter pack is extended at least 2 to 10 ft above the top of the screen. The filter pack should not extend into an overlying formation, because this would permit downward vertical seepage in the pack and either dilute or add to the contamination of the water being monitored. See Table 12.9 for a comparison of bentonite and cement grouts. Polymeric fluids are not recommended as an alternative to bentonite or cement because they contain so few solids. See Chapter 10 for grout placement procedures.

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bentonite</td>
<td>* Readily available</td>
<td>* May produce chemical interference with water-quality analysis</td>
</tr>
<tr>
<td></td>
<td>* Inexpensive</td>
<td>* May not provide a complete seal because:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>— There is a limit (14 percent) to the amount of solids that can be pumped in a slurry. Thus, there are few solids in the seal, should wait for liquid to bleed off so solids will settle</td>
</tr>
<tr>
<td></td>
<td></td>
<td>— During installation, bentonite pellets may hydrate before reaching proper depth, thereby sticking to formation or casing and causing bridging</td>
</tr>
<tr>
<td></td>
<td></td>
<td>— Cannot determine how effectively material has been placed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>— Cannot assure complete bond to casing</td>
</tr>
<tr>
<td>Cement</td>
<td>* Readily available</td>
<td>* May cause chemical interference with water-quality analysis</td>
</tr>
<tr>
<td></td>
<td>* Inexpensive</td>
<td>* Requires mixer, pump, and tremie line: generally more cleanup than with bentonite</td>
</tr>
<tr>
<td></td>
<td>* Can use sand and/or gravel filter</td>
<td>* Shrinks when it sets: complete bond to formation and casing not assured</td>
</tr>
<tr>
<td></td>
<td>* Possible to determine how well the cement has been placed by temperature logs or acoustic bond logs</td>
<td></td>
</tr>
</tbody>
</table>

Table 12.9. Grouting Materials for Monitoring Wells

For monitoring wells drilled by cable tool rigs, contaminant migration in the borehole can generally be eliminated by the well design shown in Figure 12.10. The 6-in casing is first installed into the clay layer. After flushing the casing and changing the drilling fluid, the borehole is extended using 4-in casing. A 2-in monitoring well is then installed and filter packed. Before installing the pack the well bore should be thoroughly flushed. As the Win temporary casing is extracted, cement or bentonite grout is placed as shown in Figure 12.10. A protective surface casing with a locking cap is installed before the cement has hardened. Normally the locking cap will be vented. The well should then be developed as thoroughly as possible.

If the well is drilled by rotary methods, a 4-in casing can be grouted in an 8-in borehole that is drilled through the contaminated aquifer into an underlying impermeable layer. After the grout has hardened, the borehole is continued inside the 4-in casing to the desired depth. A 2-in casing and screen is filter packed and then grouted in the 4-in casing.
In saline environments, a Dowell seal ring gasket (manufactured by Dow Chemical) may be used in place of bentonite, because bentonite will not hydrate in a highly saline environment. These gaskets can be made in variable lengths and mounted on the casing just prior to the installation of the screen. They are suitable for use in regularly shaped boreholes and where the organic and inorganic compounds in the gasket do not interfere with the chemical analysis of the water in the well. Cement can be placed above the gaskets to complete the seal.

A cement seal around the top of the well bore is recommended even if the annular seal is carried to the surface. The cement seal is shaped so that surface water flows away from the casing. If plastic casing is used, a short section of metal surface casing should be installed around the top section of the plastic pipe and extended 3 to 5 ft into the ground. The metal casing prevents accidents damage to the plastic pipe. The top of the casing should be fitted with a locking cap.
Frost heaving can be a major problem for small diameter PVC monitoring wells installed in cold climates. As the soil freezes during the winter, it expands upward, occasionally pulling the casing apart. Damage caused by fast heaving can be minimized by placing a metal surface casing to a depth of 5 to 10 ft. A steeply inclined cement cap should be placed around the surface casing. If frost action exerts pressure on the cement, the surface casing can rise without disturbing the monitoring well casing.

Development is especially important for monitoring wells, because drilling fluid residues remaining in the borehole will affect the chemistry of the water samples. Figure 12.11 shows that the presence of bentonite affects the chemical analyses of samples for at least 90 days after completion of the well. More thorough development shortens the time the bentonite will affect water quality. In some cases, the impact of drilling fluid additives on sampling chemistry can last for 1 to 2 years.

It should be stressed that all monitoring wells must be developed as thoroughly as possible, not only to remove all traces of the drilling fluid from the formation, but also to increase the yield so that reliable samples can be collected in the shortest time. Development is also important to assure that the ambient water quality is maintained in the sample container until the water can be analyzed. Any sediment in the sample container, for example, can react with the water, thereby altering the actual chemical quality.
### 12.9. SAMPLING MONITORING WELLS

Sampling of monitoring wells will usually be done by field personnel from the testing laboratory or by groundwater consultants. Nevertheless, drilling contractors should have an appreciation of the difficulties in sampling protocol. In general, a sample is taken only after the pH, electrical conductivity, and temperature of the water being pumped from the well have stabilized. The methodology used in the sampling procedure is critically important if the true chemical nature of the groundwater contamination at that site is to be determined. Samples may not be representative of groundwater conditions for the following reasons:

1. The sample was taken from stagnant water in the well, which is usually different chemically from water in the ground near the well bore. The transmissivity of the aquifer should be determined so that the consultant can estimate the time required to remove enough water to obtain a reliable sample. In most wells, a sample is taken after 3 to 10 well-bore volumes have been removed.

2. Samples were not taken at appropriate intervals. Sampling intervals are usually established based on the hydraulic conductivity of the formation—the faster the rate of contaminant movement, the more often samples are taken.

3. The water sample was contaminated by entrained sediment because the well was not developed properly. When the sample is acidified for preservation, contaminants adhering to the sediment, especially metallic ions, are released into the sample.

4. Sample accuracy was adversely affected by the hydraulic character of the formation. A representative sample may not be obtained when the formation has a high hydraulic conductivity near the screen and the contaminant is concentrated near the static water level in less permeable material. In this case, the proportion of uncontaminated water is so high that the dilution is sufficient to mask the presence of the contaminant.
5. The sample was taken so long after pumping began that it represents water so far from the well site that the groundwater chemistry is not representative.

6. Release of carbon dioxide during pumping caused an increase in pH which in turn caused many metallic ions to come out of solution (iron, manganese, magnesium, cadmium, arsenic, selenium, and boron).

7. Numerous chemical changes took place because the sample was oxidized during recovery. Oxidation can occur in the pomp or can be caused by water cascading into a well installed in tight formations. Because many groundwaters are in a reduced state, some of the changes that can be expected include:
   a. Oxidation of organics
   b. Oxidation of sulfide to sulfate
   c. Oxidation of ferrous iron and precipitation of ferric hydroxide \([\text{Fe(OH)}_3]\)
   d. Oxidation of ammonium ion to nitrate
   e. Oxidation of manganese and precipitation of manganese dioxide or similar hydrous oxides. The water sample became contaminated by chemical residues in the pump or sampling equipment. If sample recovery equipment is not dedicated to a single well, it must be thoroughly cleaned each time it is used.

8. The sample was not preserved correctly, so chemical changes occurred in the sample container during storage. Most samples requiring laboratory analysis are preserved by immediately wrapping with foil to prevent light from reaching them and then storing temporarily in a cold environment.

9. The sample was not analyzed quickly enough because either it did not reach the laboratory within a reasonable time or the lab could not perform the analytical tests soon enough because of poor scheduling.

10. The testing procedures at the laboratory were not set up properly and therefore did not yield accurate results. The concentration of a particular contaminant may be in the parts per billion or even parts per trillion range and the least malfunction in the analytical work can produce erroneous results. Good testing procedures include sending split samples to different labs to compare results and submitting spiked samples periodically to check the reliability of a particular lab's testing procedures. A spiked sample usually contains one or more chemicals that have been purposely added at specific concentrations.

The single most important parameter affecting the chemical quality of groundwater is pH and any disturbance in pH during sampling can cause a distinct change in chemistry. In general, air-lift or nitrogen-lift pumps produce the largest increases in pH during sampling by stripping excess dissolved carbon dioxide from the-water. Peristaltic and diaphragm pumps and bailers had less effect on pH. Air-lift pumps also reduce the concentration of volatile organic compounds. It is a good idea to measure oxidation-reduction potential (Eh), pH, and specific conductance in the field in a closed cell to determine their values as accurately as possible.

In conclusion, sampling procedures are highly complex and must be tailored to fit the chemical being monitored, the hydrogeologic situation, and the design of the monitoring well. The presence of stagnant water in the well bore will usually have an adverse effect on
the accuracy of the analysis, but time constraints may limit the number of well-bore volumes that can be removed before sampling.

12.10. THE TASK OF GROUNDWATER PROTECTION

Contamination of groundwater is more serious than surface-water pollution because it is more difficult to detect in a timely manner, moves more slowly, and requires special expertise to predict the path and rate of contaminant movement. In addition, the complex geochemical reactions taking place in the subsurface between myriad contaminants and earth materials are not well understood, and thus the ability to predict the concentration of a contaminant at any point is limited. The drilling contractor can take an active role in early detection of contaminant problems by being aware of well-known pollution sources and the various chemical and biological indicators that may indicate that contamination is occurring.

Ideally, contamination should be prevented from occurring. Successful prevention means that potential contaminants must be controlled so they cannot react with the groundwater system. Land-use planning is a major form of prevention in which the producers of hazardous wastes are kept away from areas overlying groundwater resources so that, in the event of an accidental spill, little damage will occur. When potential producers of contaminants are discovered in a community or are allowed to build new facilities, action should be undertaken to develop monitoring networks that will identify ineffective disposal practices that could affect groundwater quality. Vadose-zone sampling equipment should be placed close to waste sites so contaminants can be detected as soon as possible—preferably before they enter the local groundwater system. Monitoring wells should be installed at appropriate places around the waste site to detect any contaminants reaching the groundwater system. Once a contaminant reaches the groundwater, hydrogeologists should be consulted to determine the direction and rate of plume movement.

After a contaminant or several contaminants are found in groundwater a decision must be made on whether to rehabilitate the aquifer or find alternative groundwater resources. In some cases, no remedial methods may be undertaken because the areal extent of the contamination is limited or the concentration of the contaminant is below health-effect standards. Occasionally, indirect remedial methods may be most suitable; for example, if a new groundwater supply is available, the contaminated one can be abandoned. In direct remedial methods, the soil and groundwater are treated to eliminate the contamination, or the source is removed and the groundwater allowed to recover naturally through time. In many instances, however, the renovation cost may exceed the community's ability to pay for it.

In the past, the projected costs for restoration were usually sufficient to spur the search for other water resources because new or deeper wells could be constructed at less cost than an aquifer cleanup. When new water resources are not available, however, the costs for restoration become secondary. Fortunately, some techniques used in construction and dewatering practice have been combined with new chemical treatment methods to not only contain the spread of contamination but also to begin the restoration of the aquifer.

12.11. AQUIFER RESTORATION

Once contamination of a local groundwater supply has occurred, some action must be taken to (1) find and eliminate the source, (2) contain the contaminants in the area already affected,
and (3) restore the water quality of the aquifer. Because groundwater may be the only fresh-water resource in many areas, restoration of the aquifer may be of the highest priority regardless of the costs involved. Protection and restoration of groundwater resources must be a major concern for drilling contractors, and they should become familiar with the options available to handle contamination problems. Not only can drillers advise communities on how to solve their groundwater contamination problems, they may also become involved in the process itself.

All aquifer restoration projects have some general similarities. They are costly to perform, are time consuming to plan and implement, may be only partially effective, and litigation surrounding the contamination may prevent a full disclosure of the facts.

Containment of the contaminant source is the first step in aquifer restoration. Recent research has shown that virtually all landfills leak, even if various types of plastic liners or clay layers have been used to retain the leachate. Capping of abandoned landfill sites with bentonite or other low-permeability material prevents rainwater from entering the site, thus eliminating the formation of leachates.

A combined method of containment and abatement is one way to effect aquifer restoration. Containment usually focuses on some hydraulic means of preventing the spread of the contaminant either through withdrawal of contaminated water or the injection of clean water to create a pressure ridge. Withdrawal of groundwater can reverse the local groundwater gradient, thereby preventing the advance of the contaminant front. The water removed is usually treated before use or is discharged to a surface-water body, where dilution takes place. Contaminant plumes can also be contained by injecting large volumes of water to create a local high in the potentiometric surface.

Slurry walls can also be used to isolate areas of contaminated groundwater. Slurry walls consist of bentonite, water, and backfill material placed in deep trenches. The mixture of soil material and hydrated bentonite can be placed deeper than 100 ft. This method is particularly successful if the slurry walls can be tied into an underlying impermeable formation. Rainwater percolating into the area isolated by the slurry walls is removed by wells to keep the contaminated water from overtopping the walls. This water can be treated and then reinjected downgradient. Steel sheet piling can also be used to construct cut-off walls to contain groundwater contamination.

Ordinarily, a slurry wall will last 20 to 40 years or even longer. However, the service life of the slurry wall is greatly affected by the type of chemicals in the groundwater. Organic chemicals, for example, can cause a great increase in the hydraulic conductivity of a slurry wall in only a few years.

Some wastes are so dangerous and long lasting that the only effective way to prevent long-term groundwater contamination is to excavate the material, treat it, and replace it or to simply haul it away to a safe disposal site. Where either of these options is not feasible, the wastes are sometimes completely encapsulated by impermeable materials and left permanently at the site. In other cases, chemical alteration of a contaminant in the ground can sometimes be done successfully in relatively small areas.
In many areas where various types of synthetic organic chemicals have contaminated the groundwater, new water treatment methods such as air stripping and activated carbon are used to decontaminate the water, either before use or before it is injected back into the ground. It is fortunate that many organic chemicals have a low affinity for soil particles so that the chemical remains in the water as the plume moves downgradient. Once the contaminant source has been removed and the water cleaned up or normally replaced by recharge, no large-scale contamination remains in the aquifer.

Hydrocarbon contamination results in severe taste and odor problems in wells, as well as infiltration into storm and sanitary sewers and odors in basements. Hydrocarbons can exist as free product at the top of the water table or as dissolved or emulsified product in the aquifer. After the source has been identified and the contamination stopped, removal of hydrocarbons from the surface or near surface of an aquifer involves one or more recovery wells in which a one- or two-pump system is used. Additional abatement and cleanup procedures may include the following:

1. Treatment of contaminated water in an air-stripping tower to remove volatile organics and to induce oxygenation of the contaminated groundwater.

2. Recharge of the treated groundwater by infiltration galleries to facilitate flushing and leaching of gasoline absorbed onto soil particles.

3. Reoxygenate groundwater by means of air compressors and wells to accelerate the growth of aerobic bacteria that metabolize hydrocarbons.

4. Addition of nutrients to wells to stimulate the growth of bacteria.

Standard water well design procedures are used for hydrocarbon recovery wells. High open area screens are necessary because hydrocarbons provide an environment in which bacteria can grow and thereby plug the screen. Somewhat longer screens should be used for hydrocarbon recovery because all product (hydrocarbons) floating on the water table must enter the well. Placement of the screen is also critical. Under ordinary circumstances, the cone of depression should be just large enough to recover the product. Steeper drawdown cones cause more of the hydrocarbons to become trapped in the aquifer materials (product retention in the aquifer may range from 8 to 16 percent), reducing the total volume of hydrocarbons that can be recovered.

Drilling contractors and well design engineers should become familiar with these and other effective remedial procedures so they can advise individuals and communities on ways to reduce the spread of contaminants and restore local groundwater quality.

12.1 2. CONCLUSIONS

Cleanup of contaminated aquifers is difficult, time consuming, and occasionally dangerous, depending on the nature of the contaminant. Drilling contractors should be especially careful when asked to drill in areas where venous forms of industrial waste have been deposited in the past. Many of these sites may not be posted as old dumping sites. Fortunately, the awareness of groundwater contamination problems, coupled with improved scientific