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PUBLICATION NOTICE

1. NTRP 4-04.2.13/FM 3-34.469/AFMAN 32-1072 (DEC 2008), WATER-WELL DRILLING OPERATIONS, is available in the Navy Warfare Library. It is effective upon receipt.

2. This publication provides general information for engineer personnel responsible for planning, designing, and drilling wells, focuses on techniques and procedures for installing wells, and includes expedient methods for digging shallow water wells, such as hand-dug wells.

3. Summary. Military personnel assigned to well drilling teams must have a basic understanding of groundwater principles and well drilling mechanics and hydraulics to successfully install wells. A well driller enhances his skills primarily from experience in solving problems, overcoming obstacles in the field, and learning from failures. This publication reviews common experiences well drillers encounter in the field, including well installation and completion.

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CONTENTS

CHAPTER 1 — INTRODUCTION

1.1 FIELD WATER SUPPLY ................................................................. 1-1
1.2 WATER DETECTION ................................................................. 1-2
1.3 WELL DRILLING ................................................................. 1-3
1.4 WELL DRILLING TEAMS ................................................................. 1-3

CHAPTER 2 — GROUNDWATER

2.1 FUNDAMENTALS ................................................................. 2-1
2.2 HYDROLOGIC CYCLE ................................................................. 2-1
2.3 GROUNDWATER OCCURRENCE ................................................................. 2-3
2.4 GEOLOGICAL SETTING ................................................................. 2-3
2.5 GROUNDWATER HYDRAULICS ................................................................. 2-5
2.6 AQUIFERS ................................................................. 2-11
2.7 GROUNDWATER EXPLORATION ................................................................. 2-14
2.8 DESERT ENVIRONMENTS ................................................................. 2-35
2.9 WATER QUALITY ................................................................. 2-37

CHAPTER 3 — FIELD OPERATIONS

3.1 TEAM CONCEPT ................................................................. 3-1
3.2 TEAM PLANNING, COORDINATION, AND PREPARATION ................................................................. 3-2
3.3 DEPLOYING TEAMS ................................................................. 3-3
3.4 SITE PREPARATION ................................................................. 3-4
3.5 DRILLING FLUID ................................................................. 3-5
3.6 WELL DRILLING OPERATIONS ................................................................. 3-6
3.7 SAMPLING AND LOGGING ................................................................. 3-7
CHAPTER 7 — WELL DECK AND PUMPS
7.2 SHALLOW-WELL PUMPS ................................................................................. 7-1
7.3 DEEP-WELL PUMPS ......................................................................................... 7-6
7.4 AIR-LIFT PUMPS ............................................................................................. 7-10

CHAPTER 8 — WELL-PERFORMANCE TESTING PROCEDURES
8.1 TESTING PUMPS ............................................................................................ 8-1
8.2 MEASURING WATER LEVEL .......................................................................... 8-3
8.3 MEASURING DISCHARGE RATE ..................................................................... 8-4

CHAPTER 9 — COLD WEATHER WELL CONSTRUCTION
9.1 CONSIDERATIONS .......................................................................................... 9-1
9.2 WELL DRILLING ............................................................................................. 9-2

APPENDIX A — ARMY WATER SUPPLY AND WELL DRILLING
A.1 CONCEPT ........................................................................................................ A-1
A.2 ORGANIZATION AND SCOPE ...................................................................... A-1
A.3 EQUIPMENT ..................................................................................................... A-3
A.4 FIELD WATER SUPPLY ................................................................................ A-4
A.5 REACHBACK RESOURCES .......................................................................... A-5

APPENDIX B — NAVY WELL DRILLING
B.1 CONCEPT ........................................................................................................ B-1
B.2 ORGANIZATION AND SCOPE ...................................................................... B-1
B.3 EQUIPMENT ..................................................................................................... B-1

APPENDIX C — AIR FORCE WELL DRILLING
C.1 CONCEPT ........................................................................................................ C-1
C.2 ORGANIZATION AND SCOPE ...................................................................... C-1
C.3 EQUIPMENT ..................................................................................................... C-1

APPENDIX D — WATER RESOURCE DETECTION TEAM
D.1 CONCEPT ........................................................................................................ D-1
APPENDIX E — FORMS

E.1 WELL DRILLING FORMS.........................................................................................................................E-1
LIST OF ILLUSTRATIONS

CHAPTER 2 — GROUNDWATER

Figure 2-1. Hydrologic Cycle .............................................................. 2-2
Figure 2-2. Water Flow from Recharge to Discharge Areas ......... 2-2
Figure 2-3. Mississippi River Basin .................................................. 2-3
Figure 2-4. Hydrographic Basin ......................................................... 2-4
Figure 2-5. Porosity Percentage (values in percent by volume) .......................................................... 2-5
Figure 2-6. Primary and Secondary Openings ......................... 2-6
Figure 2-7. Hydraulic Conductivity .................................................. 2-6
Figure 2-8. Hydraulic Conductivity of Rocks and Soil .............. 2-7
Figure 2-9. Specific Yield and Retention Percentages (values in percent by volume) 2-8
Figure 2-10. Specific Retention ........................................................ 2-8
Figure 2-11 (A/B). Difference between Hydraulic Connectivity and Transmissivity 2-9
Figure 2-12. Drawdown ................................................................. 2-10
Figure 2-13. Hydraulic Gradient ...................................................... 2-10
Figure 2-14. Unconfined Aquifer ..................................................... 2-12
Figure 2-15. Flowing Artesian Well ................................................. 2-12
Figure 2-16. Perched Water Table ................................................... 2-12
Figure 2-17. Catchment ................................................................. 2-13
Figure 2-18. Karst Topography Carbonate Aquifer .................. 2-14
Figure 2-19. Water Flow through Lava ............................................ 2-15
Figure 2-20. Hydrogeologic Indicators for Groundwater Exploration 2-16
Figure 2-21. Rocks in Groundwater Hydrology ....................... 2-17
Figure 2-22. Alluvial Valley ........................................................... 2-18
Figure 2-23. Water in a Coastal Terrace ...................................... 2-19
Figure 2-24. Alluvial Fan ............................................................... 2-20
Figure 2-25. Alluvial Basin .............................................................. 2-20
Figure 2-26. Glaciated Region ......................................................... 2-21
Figure 2-27. Hydrogeologic Stratigraphic Column of the Great Basin 2-22
Figure 2-28. Structure Map of Western Iran ................................. 2-23
Figure 2-29. Faults and Springs ....................................................... 2-23
Figure 2-30. Effects of Consolidation on Porosity and Permeability 2-24
Figure 2-31. Landforms and Hydrogeologic Characteristics .......... 2-26
Figure 2-32. Stream Drainage Patterns .......................................... 2-27
Figure 2-33. Hydrographic Basin with Recharge Areas ............ 2-27
Figure 2-34. Mounding ................................................................. 2-28
Figure 2-35. Hydrographic Basin with Discharge Areas ............ 2-29
Figure 2-36. Groundwater Flow from Recharge to Discharge Areas 2-29
Figure 2-37. Types of Springs ........................................................ 2-30
Figure 2-38. Plant Information ........................................................ 2-32
Figure 2-39. Playas and Salt Encrustation Deposits .................. 2-33
Figure 2-40. Pivot Irrigation Patterns .............................................. 2-34
Figure 2-41. Geologic Features in an Intermountain Valley ....... 2-35
Figure 2-42. Desert Mount and Plain Terrain .............................. 2-36
Figure 2-43. Oasis .......................................................... 2-36
CHAPTER 6 — WELL-COMPLETION PROCEDURES

Figure 6-1. Well Development Methods ................................................................. 6-2
Figure 6-2. Jetting Tool on Bottom of Drill String .................................................... 6-2
Figure 6-3. Surge Block ....................................................................................... 6-3
Figure 6-4. Recommended Pipe Sizes for Air-Lift Pumping ................................. 6-4
Figure 6-5. Placing the Drop Pipe and Air Line in the Well ................................. 6-5
Figure 6-6. Arranging Equipment to Build Up Air Pressure ............................... 6-6
Figure 6-7. Sacrificial Anode .............................................................................. 6-9
Figure 6-8. Concrete Platform ............................................................................ 6-10
Figure 6-9. Sample Well-Completion Summary Report ....................................... 6-12

CHAPTER 7 — PUMPS

Figure 7-1. Guide to Pump Selection .................................................................. 7-2
Figure 7-2. Pitcher Pump ..................................................................................... 7-3
Figure 7-3. Rotary Pump ...................................................................................... 7-4
Figure 7-4. Centrifugal Pump .............................................................................. 7-4
Figure 7-5. Self-priming Pump ........................................................................... 7-6
Figure 7-6. Submersible Pump ........................................................................... 7-7
Figure 7-7. Turbine Pump .................................................................................... 7-8
Figure 7-8. Helical-Rotor Pump .......................................................................... 7-9
Figure 7-9. Jet Pump .......................................................................................... 7-10
Figure 7-10. Air-Lift Principle .......................................................................... 7-11
Figure 7-11. Air Pipe in an Eductor Pipe ............................................................. 7-12
Figure 7-12. Submergence Percentage ............................................................... 7-13
Figure 7-13. Pump Readings ............................................................................. 7-14
Figure 7-14. Submergence for Air-Lift Pumping .................................................. 7-15

CHAPTER 8 — WELL-PERFORMANCE TESTING PROCEDURES

Figure 8-1. Cubic Feet of Air Requirements for Various Submergences and Pumping Lifts .................................................. 8-3
Figure 8-2. Constants ....................................................................................... 8-3
Figure 8-3. Sounder ......................................................................................... 8-4
Figure 8-4. Steel-Tape Measurement Method .................................................... 8-4
Figure 8-5. Open-Pipe Flow Measurement Method .......................................... 8-5
Figure 8-6. Open-Pipe Flow Measurements ...................................................... 8-6
Figure 8-7. Correction Factors ......................................................................... 8-6

CHAPTER 9 — COLD WEATHER WELL CONSTRUCTION

Figure 9-1. Unfrozen Strata ................................................................................. 9-1
Figure 9-2. Percussion-Type Drilling Rig ............................................................. 9-3
Figure 9-3. Jet-Drive Point ................................................................................. 9-4
Figure 9-4. Specific Gravity of Drilling Fluids................................................................. 9-5

APPENDIX A — ARMY WATER SUPPLY AND WELL DRILLING

Figure A-1. Well Drilling Headquarters (05520LD00)..................................................... A-2
Figure A-2. Well Drilling Team (05520LE00)................................................................. A-3
Figure A-3. 600-ft Well Drilling System and Specifications.......................................... A-4
Figure A-4. Army Reachback Contact Information....................................................... A-6

APPENDIX B — NAVY WELL DRILLING

Figure B-1. T2W Well Drilling Machine ................................................................. B-2
Figure B-2. T2W Specifications ................................................................................. B-3

APPENDIX C — AIR FORCE WELL DRILLING

Figure C-1. Air Force RED HORSE Program Contact Information............................. C-2

APPENDIX E — FORMS

Figure E-1. Well Drillers Log.................................................................................... E-2
Figure E-2. Piping and Casing Log............................................................................ E-4
Figure E-3. Military Water-Well-Completion Summary Report............................... E-6
PREFACE

The provisions of this publication are the subject of international standardization agreement (STANAG) 2885 ENGR (Edition 4), *Emergency Supply of Water in War*. Throughout this publication, references to other publications imply the effective edition.

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The following definitions apply to warnings, cautions, and notes used in this manual:

**WARNING**

An operating procedure, practice, or condition that may result in injury or death if not carefully observed or followed.

**CAUTION**

An operating procedure, practice, or condition that may result in damage to equipment if not carefully observed or followed.

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An operating procedure, practice, or condition that requires emphasis.
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Word usage and intended meaning throughout this publication is as follows:

“Shall” indicates the application of a procedure is mandatory.

“Should” indicates the application of a procedure is recommended.

“May” and “need not” indicate the application of a procedure is optional.

“Will” indicates future time. It never indicates any degree of requirement for application of a procedure.

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CHAPTER 1

Introduction

1.1 FIELD WATER SUPPLY

Maintaining a constant supply of water is critical to sustaining the force. Beyond military consumption, a water supply is critical for chemical, biological, radiological, or nuclear (CBRN) decontamination, sanitation, construction, medical operations, and equipment maintenance. The quantity and quality of water required depends upon climatic conditions, terrain, and the type of operation conducted.

In an operational area (OA), the tactical or installation commander provides water support requirements to general engineer (GE) units under the combat service support (CSS) element. The CSS element is tasked in turn to provide water. Requests for well drilling support go through operational channels to higher headquarters (HHQ).

Tactical and logistical personnel plan and coordinate water support functions. They ensure that sufficient water production and distribution assets are available to continuously support the forces in the OA. Planners should consider the following items when locating well sites:

1. Tactical situation
2. Geographical OA
3. Impact of well on other wells utilizing the same aquifer
4. Location of existing water sources
5. Size of the force being supported
6. Planned force deployment rates
7. Dispersion of forces in a geographic area
8. Water consumption rates and anticipated well capacity
9. Availability of transportation to move well drilling equipment and well-completion materials
10. Logistical support and main supply routes
11. Availability of assets for water distribution
12. Time required for drilling and preparing a well for production
13. Environment impact or contamination
14. Water purification assets.
Groundwater sources are normally used to supplement surface-water sources. GE support in the form of well drilling by engineers is provided to the water collection and distribution process. Specific considerations necessitating well drilling are:

1. When surface sources of water are not available in enough quantity or quality to support the force. This is likely to occur in arid terrain where the quantity of water required is high and surface sources are low. In arid environments, exploring and using groundwater can reduce the need to transport water to a desired location.

2. If the distribution system is insufficient to support the force, haul distances may be significantly reduced by a well drilled close to the consumer.

3. CBRN or other type of contamination is expected that would render surface sources unusable.

4. The mission is part of a humanitarian and civic assistance (HCA) and/or foreign humanitarian assistance (FHA) mission. A major portion of the world’s population lacks a readily available source of potable water. Providing a potable source by conducting well drilling operations (OPS) may be the decisive operation in stability and/or reconstruction operations and a critical part of the overall information operations campaign.

1.2 WATER DETECTION

1. Responsibilities. In an undeveloped or a developed OA, terrain analysts, ground-survey teams, and well drilling teams identify surface-water and groundwater sources. Water detection for all Service water-well drilling teams is typically achieved either through contract or by the Army’s Water Detection Response Team (WDRT). Refer to Appendix D for details on the WDRT. Engineer ground-survey teams determine whether a groundwater source is adequate and accessible for development.

2. Procedures. Analysts use surface water, groundwater, and existing-water-facilities overlays from the worldwide Department of Defense (DOD) Water Resources Database (WRDB) maintained by the Army. Refer to Appendix D for details on the WDRB. Surface- and existing-water-facilities water sources are identified primarily from maps and visual inspection. Groundwater sources are identified by analyzing information from groundwater-resources overlays, maps, aerial imagery, terrain studies, hydrologic and geologic data, well drilling logs, and local-national sources. Two methods of locating groundwater are:

   • Method 1. WDRTs or contractors, equipped with special devices that use geophysical techniques (electrical resistivity and seismic refraction), may be deployed to locate groundwater.

   • Method 2. Well drilling teams may drill exploratory or test wells to detect groundwater. Georesistivity testing is an option if the resources are available in theatre and time or funding allows.

Globally the demand for safe drinking water is not being met. According to the United Nations Environmental Programme report Our Planet, the uneven distribution and increasing demand creates regions of water stress. Currently 40 percent of the world’s population, about one billion people, is under water stress and will increase to 67 percent by 2025. Another billion people live in regions with adequate water supply but cannot afford water.

“Freshwater,” Our Planet, 2003
The second method is accurate but time consuming. Teams should use this method only if all other water-detection methods are unsuccessful or are not available. The methods used for detecting water depend on the urgency for finding groundwater and the resources available. Speed and accuracy are essential for locating water in any OA.

3. **Equipment.** The WDRT’s water-detection equipment is deployable by air, sea, or ground transport into a developed or undeveloped OA.

### 1.3 WELL DRILLING

Wells provide water to the deployed forces in an undeveloped OA, to the forward deployed units in a developed theater, and to the forces that occupy permanent or semipermanent installations in a developed OA. Wells are located and drilled in secure areas in an installation or in the OA by Service water-well drilling teams as discussed in Paragraph 1.4.

1. **Forward Deployed Forces in a Developed OA.** Well drilling OPS support forward deployed forces and force buildup in a developed OA. Groundwater sources supplement, but do not replace, surface water sources. Well drilling teams conduct well drilling OPS during all phases of an operation. Rapid movement of the well drilling team into the OA is not essential. Teams with organic equipment arrive at the OA primarily by sea or ground from prepositioned locations. The teams may depend on supported units for logistical and administrative support. Transportation support is also usually required for movement of well drilling equipment and components.

2. **Permanent or Semipermanent Fixed Installation Forces in a Developed OA.** These installations are located in built-up or rural areas where water sources may be available. Groundwater sources supplement existing water sources to meet installation water requirements. The wells are permanent. The facilities engineer manages all water utilities on an installation.

3. **Combat Zone.** The OPS Officer of the supporting unit the well drilling team is attached to coordinate OPS with the supported unit. When the well drilling team completes a well, they turn it, all installed equipment and technical specifications over to the OPS Officer. The OPS Officer then turns the operation over to the supported unit. Unless other arrangements are made in advance, the supported unit is responsible for:
   
   a. Drawing water from the stave tank to purify, treat, store, and distribute water.

   b. Operating all equipment at the well site, to include the well pump and generator.

   c. Maintaining all equipment except the well pump and screens.

   Any well repair or maintenance that exceeds the capability of the supported unit must be coordinated through the staff engineer that supports the OA.

4. **Communications Zone (comms).** The well drilling team’s OPS section coordinates OPS with supported units, civil affairs personnel, or host nation (HN) support (HNS) units as required. When the well-drilling team completes a well, they turn over the operating well, all installed equipment, and the technical specifications to the OPS Officer, who then turns the operation over to the facilities engineer. The facilities engineer coordinates with supply planners, civil-affairs personnel, or the HN regarding well OPS and maintenance. HNS is used whenever possible to support well drilling OPS.

### 1.4 WELL DRILLING TEAMS

To accomplish the well drilling mission, well drilling teams (with organic equipment) are deployed to the OA by air, sea, or ground. Each team has a truck- or semitrailer-mounted drilling machine. They use these machines to reach deep aquifers and develop wells. Teams also have well-completion kits. Kits include the casing, screen,
pumps and generators, and other necessary equipment needed to provide an aquifer-to-storage-tank capability. The teams may depend on supported units for logistical and administrative support. Transportation support is also usually required to move well drilling equipment and components.

1. **All Service well drilling teams are able to do the following, at a minimum:**
   a. Disassemble, transport, and reassemble the drilling rig.
   b. Set up the well drilling rig and support equipment.
   c. Drill up to a 1,500-foot, 15-inch diameter well (Army equipment is 600 feet (ft) adaptable to 1,500 ft with additional air compressor set up).
   d. Drill with mud, air, and foam circulation.
   e. Drill with a down-the-hole hammer.
   f. Drill in sand, soil, clay, rock, or other geological formations.
   g. Perform operator’s service checks and maintenance.
   h. Develop the well for connecting and interfacing with storage facilities and water-distribution systems.

2. **Refer to the following appendices for information on Service-specific well drilling teams and OPS:**
   a. *Army*. See Appendix A.
   b. *Navy*. See Appendix B.
   c. *Air Force*. See Appendix C.
CHAPTER 2

Groundwater

2.1 FUNDAMENTALS

To locate and evaluate water sources, team leaders must know about the earth’s topography and geologic formations. Surface sources of water, such as streams, lakes, and springs, are easy to find. Reconnaissance personnel are responsible for locating surface-water sources and for providing adequate water supplies to troops in the field. Groundwater sources often require more time to locate. Geologic principles can help engineers locate groundwater supplies and eliminate areas where no large groundwater supplies are present. About 97 percent of the earth’s fresh water (not counting the fresh water frozen in the polar ice caps and glaciers) is located underground. Most of the groundwater tapped by water wells is derived from precipitation on the earth’s surface.

2.2 HYDROLOGIC CYCLE

The constant movement of water above, on, and below the earth’s surface is the hydrologic cycle (see Figure 2-1). The concept of the hydrologic cycle is that precipitation returns again to the atmosphere by evaporation and transpiration. Understanding this cycle is basic to finding groundwater. Three-fourths of the earth’s surface is covered by ocean water. Direct radiation from the sun causes water at the surface of the oceans to change from a liquid to a vapor (evaporation). Water vapor rises in the atmosphere and can accumulate as clouds. When the clouds accumulate enough moisture and conditions are right, the water is released in the form of rain, sleet, hail, or snow (precipitation).

1. **Recharge and Discharge.** Precipitation on land surfaces may be stored on the surface. It also flows along the surface (runoff) or seeps into the ground (infiltration). Surface storage is in lakes, ponds, rivers, and streams and is snow and ice. Polar ice caps and glaciers store 85 percent of the earth’s fresh water. Runoff provides the main source of water for streams and rivers. Water infiltrating into the soil is the major source of groundwater. Water that seeps into the ground recharges groundwater resources.

As groundwater moves from the recharge area, it may discharge back to the surface. Groundwater flows from recharge areas to discharge areas where the water is discharged to lakes, rivers, springs, and oceans (see Figure 2-2). Another form of discharge is the consumption of water by plants and animals. Plants draw large quantities of water from the soil and return this water to the atmosphere (transpiration). Man also causes water discharge for consumption.

2. **Water Storage.** Water wells are constructed to produce water supplies from groundwater reserves. Developing a groundwater supply has many advantages over using surface water. Groundwater is more abundant than surface water, is often cleaner, requires less treatment, and may be easier to protect than surface-water supplies. A water well is easy to seal from natural contamination and to protect from clandestine contamination. Groundwater supply remains unaffected by short-term drought unless it relies directly on surface sources.
Figure 2-1. Hydrologic Cycle

Figure 2-2. Water Flow from Recharge to Discharge Areas
2.3 GROUNDWATER OCCURRENCE

The hydrologic cycle exists on global and local levels. By understanding the local hydrologic cycle, it is possible to predict the directions and rates of groundwater flow, to identify groundwater resources, and to select development areas. An area drained by a stream or river is a drainage basin. For example, the Mississippi River Basin includes most of the area between the Rocky and Appalachian Mountains (see Figure 2-3). Major river basins are subdivided into smaller basins. The Missouri and Ohio River Basins are regional subdivisions of the Mississippi River Basin. These subdivisions can also be divided into local drainage basins (hydrographic basins) for each tributary (see Figure 2-4). The boundaries of hydrographic basins are usually represented by mountains or hills, which restrict the flow of water, and by low areas where the water is discharged out of the basin.

The depth to groundwater may range from very near the surface to more than 1,000 ft. In most arid areas, the shallowest groundwater sources occur in recharge and discharge areas. Precipitation over mountainous areas results in a groundwater recharge at the base of the mountains into alluvial valleys. Precipitation over a mountainous area results in higher runoff and lower groundwater recharge ratios on the slopes of mountainous terrain. Even though groundwater may be shallow in these areas, the rough terrain and the rocks make mountainous areas difficult sites for water wells. Although mountainous areas are presumed to be recharge areas, military engineers do not normally drill tactical water-supply wells on mountain sides.

2.4 GEOLOGICAL SETTING

The ability of soils and rocks to hold and transmit water varies, and the depth to groundwater varies in different geological settings. Physical properties of soils and rocks, such as degree of consolidation, cementation, and hardness, determine drilling methods and the potential for groundwater production. When drilling, consolidated rock is harder to penetrate but is more stable than unconsolidated rock. Well drillers usually use a down-hole air hammer on consolidated rock with no well casing for support. Drillers must support holes in unconsolidated rock to avoid cave-ins. Wells in unconsolidated rock frequently yield more water at a shallower depth than wells in consolidated rock. The list below describes the degree of consolidation in more detail:

![Figure 2-3. Mississippi River Basin](image-url)
1. **Unconsolidated Deposits.** Unconsolidated deposits:
   
a. Cover the majority of the earth’s surface.

b. Range in thickness from a few inches to several thousand ft.

c. Can underlie consolidated rocks.

d. Consist of weathered rock particles of varying materials and sizes.

e. Include clays, silts, sand, and gravel.

f. May include salt deposits and fragments of shells of marine organisms.

2. **Consolidated Deposits (Rock).** These rocks consist of mineral particles of different sizes and shapes. Heat and pressure or a chemical reaction has formed the rocks into a solid mass (often called bedrock). Geologists classify consolidated deposits into the following three categories, depending on origin:
a. **Igneous.** These rocks form when hot molten material (magma) cools and solidifies either inside the earth’s crust or on the earth’s surface (lava). Basalt and granite are two common igneous rocks that military well drillers encounter.

b. **Sedimentary.** These rocks are composed of sediments that are converted to rock through compaction, cementation, or crystallization. Sedimentary rocks cover about 75 percent of the earth’s surface. Shale, sandstone, and limestone comprise over 95 percent of these rocks.

c. **Metamorphic.** These rocks are igneous, sedimentary, or preexisting metamorphic rocks that undergo further transformation by temperature, pressure, or chemical changes. The transformation usually occurs very deep in the earth’s crust; Schist and gneiss are common metamorphic rocks.

### 2.5 GROUNDWATER HYDRAULICS

The list below describes basic groundwater hydraulic principles:

1. **Porosity.** Soil and rock are composed of solids and voids (pores). Groundwater can fill up and flow through pores. Pores formed at the same time as the rock such as in sand, gravel, and lava tubes in basalt, are called primary openings. Pores formed after the rock was formed are called secondary openings. Examples are fractures in massive igneous rocks like granite and the caves and caverns in limestone. The pore sizes vary and may or may not be filled with water. The ratio of volume of the pore space to the total volume of the soil or rock is called porosity. Porosity is normally expressed as a percentage (see Figure 2-5). Figure 2-6 shows primary and secondary openings.

2. **Permeability.** The property of permeability is related to porosity. In qualitative terms, permeability is expressed as the capacity of a porous rock or soil to transmit a fluid. Large interconnected pore openings are associated with high permeability, while very small unconnected pore openings are associated with low permeability. Sand and gravel with large interconnected pore openings have high porosity and permeability. Clay tends to have high porosity, but the very small openings tend to inhibit the passage of water. Therefore, clay displays low permeability.

<table>
<thead>
<tr>
<th>Material</th>
<th>Primary Openings</th>
<th>Secondary Openings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equal-size spheres (marbles):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Loosest packing</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>• Tightest packing</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Gravel</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Sandstone (semiconsolidated)</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Granite</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Basalt (young)</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 2-5. Porosity Percentage (values in percent by volume)
Hydraulic conductivity is a measurement of the capacity of rock or soil to transmit water. The higher the hydraulic conductivity, the faster the water will flow at a given pressure (see Figure 2-7). Hydraulic conductivity is related to the size and spacing of particles or grains in soils or to the number and size of fractures in rocks (see Figure 2-8). The hydraulic conductivity of rocks and soil is measured by field or laboratory tests. Findings are recorded as volume of water flowing per unit area per unit of time and expressed as foot per day or centimeter per second (cps).
3. **Specific Yield and Retention.** Figure 2-9 shows specific yield and retention percentages. Only a portion of the water stored in pores can be pumped out of a well. Specific retention ($S_r$) is the water that cannot be pumped out of a well and is left as a film on the rock surfaces. Specific yield ($S_y$) is the water that can potentially be pumped from a well (see Figure 2-10). The $S_r$ and $S_y$ percentages compared to porosity indicate how much water is developable from a rock formation.
4. **Transmissivity.** Although hydraulic conductivity measures the relative flow of water through a subsurface material, the results may not be an accurate measurement of the yield that is obtainable from the material. The inaccuracy exists because hydraulic conductivity does not account for the thickness of the water-bearing unit (aquifer). For example, a well in a 100-ft-thick aquifer will produce more than a well in a 9-ft-thick aquifer provided both aquifers have the same permeability. Hydraulic conductivity is the water-transmitting capacity of a unit of an aquifer (see Figure 2-11, A). Transmissivity is the water-transmitting capacity of a unit prism (the saturated thickness) of the aquifer and usually is expressed in units of gallons per day per foot of aquifer width (see Figure 2-11, B). Wells in high transmissivity areas will produce high well yields. Wells in low transmissivity areas will produce low well yields.

5. **Yield and Drawdown.** Yield is the volume of water discharged from the well per unit of time when water is being pumped or is flowing freely. Yield is commonly measured in units of gallons per minute (gpm) and
gallons per hour (gph) for small yields or in cubic feet per second (cfs) for large yields. Yield is a measure of how readily an aquifer gives up its supply of groundwater. Drawdown is a measure of how much the water level near the well is lowered when the well is pumped. Drawdown is the difference (in feet) between the static water level and the water level when pumping (see Figure 2-12). It occurs in a cone shape radiating outward from well which is important for locating secondary wells. See Chapter 8 for methods of measuring yield and drawdown.

6. **Hydraulic Gradient.** Darcy’s Law describes the flow of groundwater and is applied to evaluate aquifer and aquifer material hydraulic characteristics. The hydraulic gradient is the change in head (water elevation) with distance. The hydraulic gradient determines the direction of groundwater flow.

To calculate the hydraulic gradient, use the following formula:

\[ i = \frac{(h_2 - h_1)}{L} \]

where:

\( i = \text{hydraulic gradient, dimensionless (slope)} \)

\( h = \text{hydraulic head, in ft.} \)

\( L = \text{horizontal distance from } h_1 \text{ to } h_2, \text{ in ft (see Figure 2-13)} \)
Figure 2-12. Drawdown

Figure 2-13. Hydraulic Gradient
Darcy’s experiments show that the flow of water through a column of saturated sand is proportional to the difference in the hydraulic head at the ends of the column. Darcy’s Law is still used as the basic principle that describes the flow of groundwater and is expressed as follows:

\[ \text{Q} = K_i A \]

where:

- \( \text{Q} \) = quantity of water discharged per unit time, in cfs
- \( K \) = hydraulic conductivity (constant factor)
- \( i \) = hydraulic gradient, in ft
- \( A \) = cross-sectional area, in square ft

7. **Aquifer Tests.** Groundwater aquifer performance and well efficiency are tested by placing boreholes through the aquifer. Testing and recording the yield and the drawdown can provide useful information to select the best pumping equipment and well screens for the actual well. Measurements of drawdown in observation wells (near the pumping well) and accurate pumping rates of the actual well will provide useful information on the hydraulic characteristics of the aquifer.

Aquifer tests provide values of hydraulic conductivity and transmissivity that better represent the actual aquifer than laboratory permeability tests conducted on small intact samples. The much greater volume of aquifer material tested in a field aquifer test takes into account secondary porosity in fractures and connected voids as well as the primary porosity of the materials. Field aquifer tests may also reveal the presence of boundary zones, which are zones of greater or lesser permeability or recharge zones that define the limits of the aquifer. Aquifer test data is useful in determining well yield (discharge) for groundwater supply and in engineering projects requiring dewatering of excavation sites and subsurface excavation.

2.6 **AQUIFERS**

Saturated rock or soil units that have sufficient hydraulic conductivity to supply water for a well or spring are aquifers. Aquifers transmit water from recharge areas to discharge areas, such as springs, lakes, and rivers. Typical aquifers are gravel, sand, sandstone, limestone, and fractured igneous and metamorphic rock. Those subsurface rock or soil units that do not transmit water readily and cannot be used as sources of water supplies are called aquicludes. Typical aquicludes are clay, shale, and unfractured igneous and metamorphic rock. Aquicludes that exist between aquifers are confining beds; meaning that the water moves only within the aquifer. The list below describes aquifer configurations in more detail:

1. **Unconfined.** These are aquifers that are partly filled with water, have fluctuating water levels, and can receive direct recharge from percolating surface water. Wells drilled into an unconfined aquifer are called water table wells (see Figure 2-14). Unfortunately, shallow, unconfined aquifers are subject to surface contamination such as farm land, industrial waste, and raw sewage.

2. **Confined.** These are aquifers that are completely filled with water and are overlaid by a confining bed. The water level in a well supplied by a confined aquifer will stand at some height above the top of the aquifer. Water that flows out of the well is called a flowing artesian (see Figure 2-15). Water rises because of the pressure that the overlying materials exert on the water and the height of the column of water driving the water through the interconnecting pores of the aquifer. The height of the column of water that is driving water through the aquifer is the head. The height that the water will rise to inside a tightly cased artesian well is the potentiometric surface and represents the total head of the aquifer.
Figure 2-14. Unconfined Aquifer

Figure 2-15. Flowing Artesian Well

Figure 2-16. Perched Water Table
3. **Perched.** These aquifers lie above an unconfined aquifer and are separated from the surrounding groundwater table by a confining layer (see Figure 2-16). These aquifers are formed by trapping infiltrating water above the confining layer and are limited in extent and development. In some arid environments, perched aquifers form sources of shallow and easily developed groundwater.

4. **Catchment.** These aquifers are formed where impervious rock underlies a zone of fractured rock or alluvium that serves as a reservoir for infiltrated water (see Figure 2-17). A catchment is a special type of perched aquifer. Catchments cannot provide large quantities of water, but they may provide easily developed groundwater for small demands or temporary supplies for drilling OPS.

5. **Material.**

   a. **Unconsolidated sediment.** Examples of sediment deposits and their sources are:

      (1) Alluvium, which comes from running water.

      (2) Glacial drift, which comes from flowing ice.

      (3) Sand dunes, which come from blowing winds.

      Sand and gravel deposits are the primary materials of unconsolidated aquifers. Alluvial deposits are prevalent in river valleys in humid environments and in dry gullies in arid environments. In many desert areas, alluvial deposits may be the primary source of groundwater. These deposits may be unconfined, confined, or perched.

   b. **Rock.** This aquifer is a mass of rock that can store and transmit groundwater.

      (1) Limestones and dolomites. These are carbonate rocks that dissolve when carbon dioxide from the atmosphere and groundwater mix to form carbonic acid. The acid dissolves and widens the fractures and bedding planes into larger rock openings. These openings may eventually develop into caves. Limestone with fractured zones develops solution channels. Caves can produce aquifers that yield appreciable quantities of groundwater (see Figure 2-18).
(2) Basalt. This may be an igneous rock which may be a productive water-bearing unit. The water flows through openings that include lava tubes, shrinkage cracks, joints, and broken or brecciated zones at the top of cooled lava flows (see Figure 2-19).

(3) Sandstone. This is consolidated or cemented sand. In unfractured sandstone, groundwater may store in the pores between individual sand grains which is recoverable through pumping. Water in sandstone may flow through bedding planes and joints.

2.7 GROUNDWATER EXPLORATION

In groundwater exploration, it is possible to predict the location of an unconfined aquifer within alluvial sediments. However, identifying these unconfined alluvial aquifers requires a detailed knowledge of sediments in the area. Usually, this information can only be obtained from existing water or oil well drilling records from the United States Army Corps of Engineers (USACE), Topographic Engineering Center (TEC), WDRT or from an exploratory drilling program. For development of water supplies in support of tactical OPS, the unconfined aquifer will be the preferable target zone. Deeper confined aquifers should be investigated if an unconfined aquifer cannot provide an adequate water supply or if the unconfined aquifer is nonpotable.

Rock aquifers should be considered for exploration only when unconsolidated aquifers are not present or are unable to provide a sufficient water supply. Identifying suitable well sites in rock aquifers is more difficult than in unconsolidated aquifers. Water development in rock aquifers is more time-consuming and costly and has a higher risk factor. However, in some areas, rock aquifers may be the only source of groundwater.
Indicators of groundwater resources are those conditions or characteristics that indicate the occurrence of groundwater. No indicator is 100 percent reliable for detecting groundwater, but the presence or absence of certain indicators aids detection possibilities. Indicators useful in identifying groundwater resources are called hydrogeologic indicators (see Figure 2-20). The list below describes different types of indicators in more detail:

1. **Reservoir Indicators.** These indicators are characteristics in soils, rocks, and landforms that define the ability of the area to store and transmit groundwater, but do not directly indicate the presence of groundwater. One of the first steps in groundwater exploration is to identify and evaluate reservoir indicators.
The size, shape, and water-bearing characteristics of a hydrographic basin are important in evaluating water resources. The characteristics could be more useful in selecting sites for ground-level study or drilling than knowing that indicators signify the presence of groundwater. Plants around a dry lake bed are good indicators of groundwater. However, dry lake beds contain very fine-grained sediments; wells in these areas usually produce low water yields and contain poor quality groundwater. The rock or soil type present could be the most important reservoir indicator as it usually defines the type of aquifer and its water-producing characteristics. For reconnaissance, it is only necessary to recognize three types of rock and one type of soil:

a. **Igneous Rocks.** These are poor aquifers except where the rocks have been disturbed by faulting or fracturing (see Figure 2-21). In many cases, these rocks are not capable of storing or transmitting groundwater and will act as a barrier to groundwater flow. In other cases, the stresses and movements of mountain building may have resulted in fracturing of the rock. Groundwater can accumulate in fractures and move through the rock if the fractures are connected. Most groundwater-bearing fractures are within 500-ft of the surface, and drilling deeper to find water in igneous rocks is not advised. Wells in these aquifers are often poor producers and are seldom developed unless no other water source is available.

b. **Metamorphic Rocks.** These areas rarely produce sufficient groundwater and are considered an effective barrier to groundwater flow (see Figure 2-21). Metamorphic rocks have poor potential for groundwater development.

c. **Sedimentary Rocks.** These areas have the greatest potential for groundwater development (see Figure 2-21). Sedimentary rocks are capable of supplying low to high yields if unfractured and moderate to high well yields if fractured. Sandstone, limestone, shale, and evaporites are the four common types of sedimentary rocks.
### Figure 2-21. Rocks in Groundwater Hydrology

<table>
<thead>
<tr>
<th>Groundwater Supply Source</th>
<th>Sedimentary Rocks</th>
<th>Metamorphic Rocks</th>
<th>Igneous Rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Large} )</td>
<td>Unconsolidated (pores)</td>
<td>Consolidated (pores, fractures, and solution openings)</td>
<td>Fractures</td>
</tr>
<tr>
<td></td>
<td>Gravel</td>
<td>Sandstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sand</td>
<td>Limestone</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dolomite</td>
<td></td>
</tr>
<tr>
<td>( \text{Moderate to small} )</td>
<td>Silt</td>
<td>Conglomerate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Till</td>
<td>Siltstone</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Coquina</td>
<td>Tillite</td>
<td></td>
</tr>
<tr>
<td>( \text{Confining beds} )</td>
<td>Clay</td>
<td>Shale</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Marl</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Sandstone. Sandstone’s ability to stem and transmit groundwater varies. If the sand grains are small and tightly cemented together, a well will have a low yield, but if the rock has been fractured extensively, a well could have a high yield. If the sand grains are relatively large and poorly cemented, moderate to high well yields may be possible.

2. Limestone and dolomites. Undisturbed limestone and dolomites are poor aquifers, but limestone may provide an excellent water source, where fractured. In some areas of the world, limestone areas are the principal groundwater sources. Fractures in limestone are more important than in other fractured rocks because when groundwater moves through the fractures, it can dissolve the rock and enlarge the fractures. This process is called dissolution. Dissolution allows the rock to store and transmit greater volumes of water than other types of fractured rocks. In most cases, limestone has been fractured and is considered the highest potential source of groundwater from rock.

3. Shale. Shale is fine-grained, does not usually store much groundwater, and does not transmit large quantities of groundwater. Where fractured, shale generally can only produce a few gpm. However, identifying shale units is important because shales may indicate that artesian conditions exist in more productive water-bearing units below or between shale layers.

4. Evaporites. Evaporites are generally capable of storing and transmitting groundwater but tend to dissolve in the water. Groundwater from evaporites is often unfit for human consumption and often not fit for any use. Because of the poor water quality, evaporites are generally considered to have poor potential for development. Because evaporites can dissolve in the water during drilling, immediate surface areas may collapse; causing potential injury to personnel and destruction to equipment. Special protective measures must be taken when developing a well in evaporites.

d. Alluvium. Groundwater is most readily available in areas under soils (unconsolidated sediments). This is largely because uncemented or slightly cemented and compacted materials have maximum pore space, are relatively shallow, and are easily penetrated. Soils deposited by running water are called alluvium. Alluvium was formed in relatively recent geologic time and is generally restricted to lowland terrain features, such as alluvial valleys, terraces along rivers, alluvial fans, glacial outwash plains, and alluvial basins and between mountains and coastal terraces. Factors that have an important bearing on groundwater yield in soils are particle size, cleanliness (percent of suspended sediment), and degree of...
sorting or gradation (e.g., clay yields almost no water; silt yields some, but very slowly; and a well-sorted, clean, coarse sand or gravel yields water freely).

(1) Valleys. Alluvial valleys are one of the most productive terrains for recovering groundwater (see Figure 2-22). Normally, sand and gravel form a large part of the stream alluvium so that wells located in the alluvium are likely to tap a good aquifer or series of aquifers. Individual aquifers do not usually extend far, and the number and depth of water-bearing sands and gravels changes rapidly from place to place.

Alluvium tends to become progressively finer downstream as the stream gradient decreases and the distance from outcrops of rock increases. In lower stream courses far from hard-rock highlands, alluvium is mostly silt and clay, with a few sand stringers. A shallow well has a small chance of striking such a sand stringer. The sands may be so fine-grained that most wells will have small or moderate yields. For large supplies, several wells or deeper wells may be needed.

(2) Stream and coastal terraces. Stream and coastal terraces are usually underlaid by gravel or sand deposits similar to floodplain alluvium. If the terraces are fairly broad and the deposits thick, they may be good water sources (see Figure 2-23). In areas, terraces are so deeply trenched by stream erosion that most of the groundwater rapidly drains out of the terrace gravels through the stream-cut slopes. Well drillers must be aware of the possibility of saltwater intrusion problems when drilling in coastal areas.

Figure 2-22. Alluvial Valley
(3) Fans. Alluvial fans are found where steep mountain slopes rise abruptly from adjacent plains (see Figure 2-24). Streams coming from the mountains drop coarse material near the apex of the fan and progressively finer material down the slope. At the toe of a large fan, the deposits are mostly silt and clay, with few sand stringers. Alluvial fans often produce groundwater at depths greater than alluvial valleys. Aquifers are abundant near mountains and often have a braided pattern with individual beds that are limited in extent. However, to reach water may require drilling several hundred feet. Large boulders, which are common at the apex of the fan, can make drilling difficult. Down the slope of a fan, aquifers get progressively thinner (pinch out). In the lower part of a large fan, test drilling may be needed to locate a productive bed.

(4) Basins. Alluvial basins are in regions where mountains alternate with structural troughs (see Figure 2-25). The products of erosion from the mountains partly fill the basins with alluvium laid down as a series of coalescing alluvial fans. The upper alluvial slopes form piedmont plains or alluvial aprons that gradually decrease in slope toward the interior of the basin until they merge with the interior flats. Lakes or playas occupying part of the central flat are usually saline. Lake-bottom deposits are largely clay. Many alluvial basins are good sources of groundwater. Good wells yield several hundred to a thousand or more gpm.

(5) Glaciated regions. Glaciated and post-glaciated areas can yield water from glacial deposits (see Figure 2-26). Large quantities of alluvium laid down by steams emerging from glaciers (glacial outwash) contain a higher percentage of gravel and coarse sand than clay. Such areas are good sources of groundwater. Extensive deposits occur in all glaciated regions of the earth, especially in the northern United States, northern Europe, and areas bordering high mountains. Many large cities, including some in the upper Mississippi basin, get their water from glacial outwash sediments.

Glacial till aquifers are generally good water-bearing units. Glacial till was deposited directly by ice into U-shaped valleys to form buried glacial valley aquifer systems – consisting of till and outwash. These may be very high producers of groundwater, and many serve as the primary drinking water source for millions of people (e.g., Dayton, Ohio). In places where outwash sands and gravels are interbedded or associated with the till, good aquifers form. Some of these aquifers may carry water under pressure.
Figure 2-24. Alluvial Fan

Figure 2-25. Alluvial Basin
e. **Stratigraphic Sequence.** The stratigraphic sequence of geologic strata that occurs in an area can give clues to the types and depths of aquifers present. Figure 2-27 shows a stratigraphic column for a portion of the arid Great Basin. The Great Basin contains a number of individual rock units. Some of these units, such as the Ely Limestone, can readily transmit water, but other units, such as the Eureka Quartzite, are relatively impermeable and cannot store or transmit exploitable quantities of groundwater. Relatively impermeable units are aquitards or aquicludes. Aquitards are units that retard or slow the passage of water.

In the stratigraphic sequence, there are five discrete aquifers and six discrete aquitards. By knowing the stratigraphic sequences in a region, it is possible to predict the type of aquifer present at a given depth. For example, the Ely Springs Dolomite is not highly fractured, but the dolomite is a productive aquifer where it is fractured. Because this unit is not overlain in the area by an aquitard, it could be an unconfined aquifer. The stratigraphic sequence indicates that the Eureka Quartzite underlies the aquifers and is an impermeable barrier or aquitard. This unit is underlain by the Pogonip Group that could provide suitable quantities of groundwater. Because this unit is overlain and underlain by aquitards, it is a confined aquifer. By using a geologic map, it is possible to estimate the thickness of each unit and the anticipated well depth. If data exists for this aquifer in other areas, it may also be possible to predict the expected well yield and groundwater quality.

In unconsolidated sediments, the stratigraphic sequence is usually less extensive, more variable, and not as well known as rock. Alluvial deposits often consist of interbedded gravel, sand, silt, clay, mixtures of these materials, and, possibly, interbedded evaporite deposits. These sediments often occur in complex stratigraphic sequences with some units discontinuous and other units grading into different soil types vertically and horizontally. Unless sufficient existing well data is available, it is impractical to define the stratigraphic sequence of such sediments.
f. Structure Density and Orientation. Geologic structures, such as folds, fractures, joints, and faults, are features that disrupt the continuity of rock units. For groundwater exploration, identifying folds has a limited use but identifying faults and fractures is important, especially in rock aquifers. The ability of rock aquifers to transmit groundwater is related to the number and size of fractures in the rock. Density of fractures is an important consideration in locating well sites in rock terrain. Figure 2-28 shows a structure map of part of western Iran. The best potential well sites are located at the intersection of fracture zones. Secondary sites are along individual fracture zones. Areas with no fractures are probably low permeability areas and poor sites for water wells.

Fracture orientation is an important characteristic of rock aquifers and of soil aquifers. Faults may act as either barriers to or conduits for groundwater flow. To distinguish between fault conduits and fault barriers, vegetative indicators are important. If a fault zone is acting as a barrier to groundwater flow, groundwater accumulates behind the barrier and often becomes shallow enough to support springs or dense stands of vegetation, or it forms wetlands (see Figure 2-29).
g. **Dissolution Potential.** Dissolution potential is the potential for the development of high secondary permeability in a soluble rock because of the dissolution of the rock through contact with groundwater. Unfractured soluble rocks, such as limestone, have a low permeability referred to as the primary permeability of the rock. Where fractured, the rock has a secondary permeability that is related to the size and density of the fractures. If the rock is soluble and saturated, the contact between the groundwater stored or moving through the fractures and the rock may result in dissolution of the rock.

The dissolution process increases the size of fractures and can result in an increased secondary permeability. Many of the world’s caves and sinkholes (karst topography) result from limestone dissolving in groundwater and are indicators of high dissolution potential. However, if such features are not present, dissolution potential must be estimated on the basis of rock type and structure density. The highest dissolution potential occurs in heavily fractured carbonates (limestone and dolomite) and evaporites. Other rock types generally do not dissolve in groundwater and identifying dissolution potential is of little use.
h. **Grain Size and Sorting.** The grain size and sorting of an aquifer is related to the porosity and permeability of the aquifer and the production capability of the aquifer. Fine-grained materials (clay) have a high porosity, but a very low permeability and are poor aquifers. Sands have moderate porosity (about half that of clay), high permeability, and are usually productive aquifers. Generally, well production capacity is directly proportional to grain size. Areas of fine-grained sediments (playas and lake beds) have poor water-production potential. Areas of coarse-grained sediments (alluvial fans) have a higher potential.

i. **Lithification.** This is the process by which sediments are converted to rock. Lithification includes compaction, consolidation, cementation, and desiccation. The degree of compaction or consolidation affects the porosity and permeability of an aquifer (see Figure 2-30). Porosity and permeability of unconsolidated materials (subjected to little or no overburden pressure) are related to grain size. With compaction and consolidation, the pore spaces between grains are reduced and the porosity and permeability of the aquifer are decreased.

Another source of lithification is the cementing of grains by the precipitation of minerals from solution in the groundwater. Many fragmented sedimentary rocks are cemented by silica or calcium carbonate precipitation from the waters they are deposited in or from waters introduced after they are deposited. Cementation often occurs along fault zones where deep mineral-rich water migrates upward. When the minerals and water mix, they precipitate travertine or other minerals along the fault zone. This can result in barriers to groundwater flow in areas selected as potential well sites on the basis of the fault zones.

j. **Drainage Basin Size.** Because most groundwater is derived from the infiltration of precipitation over an area, the size of individual drainage basins can help define the overall groundwater potential. Large drainage basins may receive more precipitation and have a larger groundwater supply than smaller basins. This is true where precipitation is the same over a region; however, it may not apply in areas of high relief, variable climate, or in arid regions.

Perhaps the most useful areas where drainage basin size can give an indication of groundwater potential is in mountainous terrain near coastal areas. In such areas, the larger drainage basins receive more recharge from precipitation. This recharge flows toward the coast and the areas of highest groundwater potential occur along the coastal plains adjacent to the larger basins. In arid environments, recharge usually coincides with areas where surface water drains from the mountainous areas and infiltrates into the groundwater system. The magnitude of this infiltration usually depends on drainage basin size and on the groundwater resource potential of the area.

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**Figure 2-30. Effects of Consolidation on Porosity and Permeability**
k. **Landforms.** Identifying landforms with drainage patterns can help identify rock types in areas without geologic maps. Landforms can provide information related to water depth, well-production potential, and water quality. Figure 2-31 lists landform classifications with hydrogeologic conditions that may be based on the presence of the landforms.

l. **Elevation and Relief.** Elevation and relief provide an idea of the amount of groundwater replenishment within a drainage basin and its groundwater potential. In a region of about the same latitude, precipitation distribution is related to the elevation of the area with zones of higher elevation receiving more precipitation than lower areas. A small drainage basin at a high elevation may receive appreciably more recharge from precipitation than a much larger basin at a lower elevation. Relief also has some effect on groundwater recharge. Areas with high relief (valleys bounded by prominent mountain ranges) have well-defined and easily identifiable recharge areas. In broad plains or plateaus, moderate relief does not indicate recharge areas; requiring other indicators (grain size or drainage density) to be used.

m. **Drainage Pattern and Density.** Recognizing drainage patterns can help define rock types, recharge areas and potential, as well as general hydrologic conditions of an area. Without geologic maps or other information on rock types, classification of the drainage pattern and landforms can provide an accurate interpretation of rock types and recognition of the area’s structure. Because most groundwater recharge occurs as infiltration of surface water drainages, areas with high drainage densities receive more recharge than areas with low drainage densities. Recognizing drainage patterns and density can provide indications of the type of aquifers, the magnitude of recharge in an area, and directions of groundwater flow. Figure 2-32 shows some of the more common drainage patterns. Rock has widely spaced rectangular or branch-like (dendritic) patterns and alluvium has medium to widely spaced parallel drainage patterns along valley areas and floodplains.

2. **Boundary Indicators.** These are characteristics that are indicative of local or regional groundwater flow systems. By identifying the boundaries of flow systems, it is possible to define directions of groundwater flow and to estimate the depth and quality of groundwater within an area. Boundary indicators do not directly indicate the presence of groundwater in an area.

a. **Recharge Areas.** These are areas where the groundwater reservoir is replenished. Recharge may be derived from the runoff of precipitation into rock fractures in mountainous areas, leakage along streambeds or under lakes, or the flow of groundwater from up-gradient areas. Figure 2-33 shows a sketch map of a hydrographic basin with identified recharge areas. Some recharge occurs in mountain areas as direct infiltration. The precipitation that does not infiltrate runs off into the local drainage network. Some recharge occurs along the streambeds and the remaining runoff discharges on the alluvial fans where it infiltrates. Precipitation over the valley floor is channeled, and quantities of recharge occur along the valley drainage system. Various amounts of recharge are derived from lakes, ponds, or channels that may occur within the basin.

The recharge of groundwater from surface water sources usually results in a mound (bulge) in the surface of the groundwater (see Figure 2-34). Groundwater in such areas flows away from the recharge sources. If the source is a lake, flow is radial away from the source. If the source is a linear source (mountain range or a stream), the groundwater divides and flow is primarily in two directions from the source. Areas recharged by direct infiltration or precipitation usually contain good quality groundwater. Groundwater under lakes may exhibit poor water quality because evaporation of lake water may increase the concentration of chemicals in the lake and any recharge derived from the lake.

Groundwater recharged from streams is usually intermediate quality between groundwater recharged by precipitation and lakes.
<table>
<thead>
<tr>
<th>Landforms</th>
<th>Hydrogeologic Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountains</td>
<td>Mountains are usually recharge areas and locations of flow system boundaries.</td>
</tr>
<tr>
<td>Mass</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td></td>
</tr>
<tr>
<td>Chain</td>
<td></td>
</tr>
<tr>
<td>Plains</td>
<td>River floodplains and playas are usually discharge areas, and have fair to poor water quality. Structural plains have little groundwater potential. Valley plains typically have good potential because of high transmissivity.</td>
</tr>
<tr>
<td>Active river floodplain</td>
<td></td>
</tr>
<tr>
<td>Structural plain</td>
<td></td>
</tr>
<tr>
<td>Playa</td>
<td></td>
</tr>
<tr>
<td>Other alluvial plains</td>
<td></td>
</tr>
<tr>
<td>Wind-formed features</td>
<td>Wind-formed features typically indicate the lack of recharge and very low groundwater potential at shallow depths although deep, confined aquifers may exist.</td>
</tr>
<tr>
<td>Yardang</td>
<td></td>
</tr>
<tr>
<td>Dune</td>
<td></td>
</tr>
<tr>
<td>Blowout</td>
<td></td>
</tr>
<tr>
<td>Water-formed features</td>
<td>Deltas and alluvial fans are recharge areas for surface runoff. Swamp, marsh, and wetlands are discharge areas and indicate shallow water. Badlands indicate the lack of a shallow water table.</td>
</tr>
<tr>
<td>Terrace</td>
<td></td>
</tr>
<tr>
<td>Alluvial fan</td>
<td></td>
</tr>
<tr>
<td>Delta</td>
<td></td>
</tr>
<tr>
<td>Swamp, marsh, and wetlands</td>
<td></td>
</tr>
<tr>
<td>Natural lake</td>
<td></td>
</tr>
<tr>
<td>Badlands</td>
<td></td>
</tr>
<tr>
<td>Marine-formed features</td>
<td>Marine-formed features indicate very shallow but saline groundwater.</td>
</tr>
<tr>
<td>Beach</td>
<td></td>
</tr>
<tr>
<td>Tidal flat</td>
<td></td>
</tr>
<tr>
<td>Man-made features</td>
<td>Man-made lakes and pits are often recharged areas as are areas adjacent to embankments and mounds. Tailings piles may be located near existing dewatering wells inside mines.</td>
</tr>
<tr>
<td>Mining pit</td>
<td></td>
</tr>
<tr>
<td>Tailings pile</td>
<td></td>
</tr>
<tr>
<td>Embankment</td>
<td></td>
</tr>
<tr>
<td>Mound</td>
<td></td>
</tr>
<tr>
<td>Lakes</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2-31. Landforms and Hydrogeologic Characteristics
Figure 2-32. Stream Drainage Patterns

Figure 2-33. Hydrographic Basin with Recharge Areas
Subsurface recharge from adjacent basins is often difficult to assess. By knowing the elevation of groundwater in adjacent areas, the transmissivity of the aquifer, and the width of the recharge area, it is possible to estimate the amount of recharge from subsurface flow. This estimate usually is not possible in areas with limited data. It is possible to infer that such flow is occurring on the basis of differences in elevation and the location of barriers or conduits between hydrographic basins.

b. Discharge Areas. Recharge to and discharge from a hydrographic basin must be equal. Figure 2-35 shows a sketch map of a hydrographic basin with identified discharge areas. Figure 2-36 shows the directions of groundwater flow from the recharge to the discharge areas. Groundwater discharge can occur in streams and lakes through consumption by plants or man and by subsurface flow to adjacent down gradient basins.

The location of discharge areas can help identify areas of shallow groundwater. Streams sustained by groundwater seepage, wetlands, and certain types of vegetation indicate discharge areas where groundwater is close to land surface. Some types of vegetation are capable of sending tap roots to depths of over 100 ft and are not indicative of shallow groundwater. The location of subsurface discharge areas requires more detailed knowledge of the hydrologic balance of the area.

c. Impermeable and Semipermeable Barriers. The quantity and rate of groundwater flow from recharge areas to discharge areas are controlled by the transmissivity of the aquifers. Impermeable barriers are those features (solid rock masses) through which groundwater cannot flow. Semipermeable barriers are those features (faults or fractured rock masses) that restrict flow but do not act as a complete barrier. Such features should be recognized because they usually form the boundaries of groundwater flow systems and, when located within a flow system, can result in areas of shallow groundwater.

d. Surface-Water Divides. Surface-water divides can form boundaries between groundwater flow systems. The mounding of groundwater under areas that receive recharge from the infiltration of precipitation causes groundwater to flow away from the recharge area. Similarly, surface water flows away from topographic highs that often correlate with groundwater recharge areas so that surface-water flow patterns usually coincide with groundwater flow patterns. The identification of surface-water divides can help define groundwater flow systems.
Figure 2-35. Hydrographic Basin with Discharge Areas

Figure 2-36. Groundwater Flow from Recharge to Discharge Areas
3. **Surface Indicators.** Surface indicators are those features that suggest the presence of groundwater. These indicators can provide information about the depth, quantity, and quality of the groundwater resources in an area; however, they do not positively indicate the presence of groundwater. The resource potential of an area is an inference on the basis of the presence (or absence) of certain indicators and particularly the association of these indicators.

a. **Springs.** Springs are effluences of groundwater occurring where the water table intercepts the ground surface. Springs are usually good indicators of the presence of shallow groundwater occurrences. However, the presence of shallow groundwater may not be indicative of a good area for well construction. Springs occur where groundwater discharges from the earth’s surface. Figure 2-37 shows several types of springs. Faults, valley-depressions, and alluvial-fan springs may discharge appreciable quantities of groundwater.

![Types of Springs](image)

Figure 2-37. Types of Springs
b. **Vegetation Type.** Certain types of vegetation (or vegetative assemblages) are associated with specific hydrogeologic environments. Some plants (phreatophytes) can only exist if their root systems are in direct contact with groundwater. Phreatophytes, such as mesquite trees, have tap roots that go down more than 100 ft. Shrubs, such as saltbush, have roots that descend only a few ft, making them excellent indicators of shallow groundwater. Figure 2-38 lists several plants that indicate the presence of shallow groundwater. The density of vegetation can help define the location of recharge and discharge areas. Dense stands of vegetation along stream channels are riparian vegetation. Riparian vegetation along streams that discharge mountainous watersheds indicates that surface water is infiltrating the streambed and recharging the groundwater. In many cases, the vegetation decreases in density after the stream reaches the valley floor. Somewhere along the streambed, the riparian vegetation assemblage gives way to the typical valley-floor vegetation.

c. **Playas.** These are dry lake beds composed mainly of clay and located in intermountain valleys (see Figure 2-39). During rainy seasons, playas may store large quantities of surface water.

d. **Wetlands.** Wetlands such as marshes, bogs, and swamps are indicative of very shallow groundwater. Although wetlands are not typical of arid environments, they have been observed in arid flow systems where groundwater accumulates behind flow barriers. Wetlands can also occur in low-lying areas where the discharge of regional spring water accumulates. The presence of wetlands is an excellent indicator of groundwater. However, wetlands generally are not suitable for water-well locations because of low permeability of wetlands soil, marginal water quality from the evapotranspiration processes of wetlands vegetation, and severe mobility constraints. Wetlands are important in groundwater detection because they usually represent regional discharge points. Areas up-gradient of wetlands are usually favorable targets for groundwater development.

e. **Streams and Rivers.** Streams and rivers (including dry streambeds and riverbeds) are usually recharge areas in arid regions and may be recharge or discharge areas in temperate climates, depending on seasonal rainfall. This type of recharge is especially true of major streams that drain the central portions of most valleys. Because recharge occurs along stream courses and streams occur in lower elevation areas in the valley, the areas adjacent to streams are considered good locations for wells, especially near the intersection of major streams. However, such locations are not always the best available areas for water wells.

Streams often migrate over large areas of the valley floor and deposit mixtures of gravel, sand, silt, and clay. Often these deposits are discontinuous and result in a vertical sequence of poorly sorted materials with low overall permeability and low to moderate well yields. Older, buried stream channels may be better aquifers because they are composed of coarser sub-grade materials and much of the surface contamination has been filtered out.

f. **Snow-Melt Patterns.** Snow-melt patterns can provide evidence of recharge areas and directions of groundwater flow. Snow packed in mountainous areas is usually a good source of recharge because slowly melting snow produces more infiltration than rainfall.

g. **Karst Topography.** Karst topography results from the dissolution of carbonate rocks by groundwater and is characterized by caves, sinkholes, closed depressions, and disappearing streams (refer to Figure 2-18). These features indicate that the rock has a very high dissolution potential and that groundwater is present. Collapse-type sinkholes (irregular, debris-filled sinkholes) usually indicate the presence of shallow groundwater because they result from the collapse of the surface materials into a dissolution cave. In some cases, the water provides evidence of the depth to groundwater.

h. **Soil Moisture.** Soil moisture content can provide some indication of recharge and discharge areas. Areas with high soil moisture are not necessarily areas with high groundwater potential and good water-well locations. Soil moisture content is related to local rainfall and to grain size. The smaller the grain size, the higher the soil moisture. Playas and lake deposits often exhibit high soil moisture but very poor groundwater potential, resulting in low well yields.
### Plant Species

<table>
<thead>
<tr>
<th>Plant Species</th>
<th>Depth of Groundwater</th>
<th>Chemical Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rushes, sedges, cattails</td>
<td>At surface or within a few feet</td>
<td>Generally good but not invariably</td>
</tr>
<tr>
<td>Giant reed grass</td>
<td>At surface or probably within 8 ft</td>
<td>Generally good but not invariably</td>
</tr>
<tr>
<td>Wild cane</td>
<td>Near surface to 10 ft or more</td>
<td>Generally good but not invariably</td>
</tr>
<tr>
<td>Giant wild rye</td>
<td>Near surface to 12 ft or more</td>
<td>Generally good but not invariably</td>
</tr>
<tr>
<td>Salt grass</td>
<td>Near surface to 10 ft or more</td>
<td>Good to very bad</td>
</tr>
<tr>
<td>Pickle weed</td>
<td>Generally within a few ft, but locally, may be as much as 20 ft</td>
<td>Generally, highly mineralized immediately under the water table, but possibly a little better in deeper water</td>
</tr>
<tr>
<td>Arrow weed</td>
<td>Surface to possibly 25 ft; heavy growth usually indicates water within 5 to 10 ft of surface</td>
<td>Generally good but not invariably</td>
</tr>
<tr>
<td>Palm trees</td>
<td>Within a few ft of the surface</td>
<td>Potable water is generally found in vicinity of healthy palms, but locally may be very bad</td>
</tr>
<tr>
<td>Willow trees</td>
<td>Surface to 12 ft or more</td>
<td>Generally good</td>
</tr>
<tr>
<td>Alkali sacaton</td>
<td>5 ft or less to 25 ft, and in places much more luxuriant where depth to water table is 5 to 15 depth</td>
<td>Good to very bad</td>
</tr>
<tr>
<td>Rabbit brush</td>
<td>Luxuriant growth indicates water table at 8 to 15 ft (locally, as shallow as 2 ft)</td>
<td></td>
</tr>
<tr>
<td>Grease wood</td>
<td>3 ft or less to 40 ft or more, abundant and luxuriant where depth is between 10 to 20 ft</td>
<td>Doubtfully, usually mineralized, but drinkable</td>
</tr>
<tr>
<td>Mesquite</td>
<td>10 ft or less to 50 ft or more</td>
<td>Generally good but not invariably</td>
</tr>
<tr>
<td>Cottonwood trees</td>
<td>Abundant groundwater, generally good within 20 ft</td>
<td>Generally good</td>
</tr>
<tr>
<td>Desert willows</td>
<td>Generally indicates shallow groundwater; local water table may be at 5 ft or more</td>
<td></td>
</tr>
<tr>
<td>Elderberry shrubs and small trees</td>
<td>Generally within 10 ft of the surface</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>15 to 60 ft, luxuriant growth where water is within 15 ft</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 2-38. Plant Information**

i. **Salt Encrustation.** Salt encrustations often occur in playas and are indicative of saline groundwater (refer to Figure 2-39). Often, salt buildups result from the evaporation of surface water and can cover many acres. Certain salt-tolerant plants may grow in such areas, indicating shallow groundwater containing high concentrations of sodium, potassium, and other soluble salts. Although salt encrustations indicate shallow groundwater, drilling for groundwater should be avoided even if water treatment equipment is available. Surface salt deposits usually indicate deep evaporite deposits. Subsurface evaporite deposits are very susceptible to collapse and should be avoided.

j. **Wells.** One of the best indicators of groundwater is existing groundwater development with well systems. Water wells are difficult to detect, especially from imagery. It is possible to detect wells indirectly from irrigation patterns. Pivot irrigation patterns (see Figure 2-40) are distinctive and are usually supplied by centrally located water-supply wells. Such features are good indications that quality groundwater is present at economic pumping depths.
Figure 2-39. Playas and Salt Encrustation Deposits

<table>
<thead>
<tr>
<th>Name</th>
<th>Terrain</th>
<th>Groundwater Table</th>
<th>Salts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sabkha</td>
<td>Coastal flat, inundated by sea water wither</td>
<td>Very near the surface</td>
<td>Thick surface salt crust from evaporating sea brines; salt usually includes carbonates, sulphates, chlorides, and so forth.</td>
</tr>
<tr>
<td></td>
<td>tidally or during exceptional floods</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Playa</td>
<td>Inland, shallow, centrally draining basin</td>
<td>Too deep for the capillary moisture</td>
<td>None if temporary lake is of salt-free water</td>
</tr>
<tr>
<td></td>
<td>of any size</td>
<td>zone to reach the ground surface, but</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>area will be temporary lake during floods</td>
<td></td>
</tr>
<tr>
<td>Salt</td>
<td>Same as playa but often smaller</td>
<td>Same as playa, but lake is salty water</td>
<td>Surface salt deposits from evaporating temporary salty lake water;</td>
</tr>
<tr>
<td>Playa</td>
<td></td>
<td></td>
<td>salts usually include chlorides and some nitrates, sulphates, and</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>carbonates</td>
</tr>
<tr>
<td>Salina</td>
<td>Same as playa</td>
<td>Near surface; capillary moisture</td>
<td>Surface crust from evaporating salty groundwater, salts include</td>
</tr>
<tr>
<td></td>
<td></td>
<td>zone from salty groundwater can reach</td>
<td>carbonates and many others</td>
</tr>
<tr>
<td></td>
<td></td>
<td>the surface</td>
<td></td>
</tr>
</tbody>
</table>
k. **Reservoirs and Lakes.** Surface water bodies provide groundwater recharge, discharge, or both. Artificial surface water reservoirs usually capture surface water and represent areas of recharge, as do natural reservoirs created by the damming of streams. Natural reservoirs in lowland areas are often formed by the discharge of groundwater from seeps along the lake bed or from springs.

l. **Crop Irrigation.** Crop irrigation indicates the use of surface or groundwater for agriculture. In most arid environments, surface water–based irrigation is located adjacent to streams and rivers. Beyond the river floodplains, agriculture is negligible. Agricultural development in areas without surface water is a good indicator of the presence of groundwater at relatively shallow depths. The leaching action of irrigated water and the use of chemical fertilizers may impair the groundwater quality in such areas.

m. **Population Distribution.** Population distribution in arid regions or sparsely populated areas is closely related to water availability. Because of the lack of resources and technical capabilities for wide-scale groundwater development projects, population centers in arid environments without surface water are usually good indicators of groundwater supplies. These centers are often located on perched aquifers with limited capabilities; the population sizes are directly proportional to the production capacities of the aquifers.

![Figure 2-40. Pivot Irrigation Patterns](image)
2.8 DESERT ENVIRONMENTS

For contingencies, water-well drillers shall become familiar with drilling OPS in an arid or desert environment. An arid environment usually has less than 300 millimeters (mm) of rainfall per year and high average daily temperatures. Most of the soils are coarse-grained with high porosity and permeability. Because of low rainfall, only deep water tables may exist. Therefore, any well drilling units and equipment or kits deployed to a desert OA should be capable of achieving maximum depth of 1,500 ft.

Generally, the more arid the region, the greater the controls the HN will place on well-drilling activities because of the potential impact of drilled wells depleting scarce aquifers. The HN may also require more detailed documentation on the water sources. Because of the amount of water consumed during desert OPS (up to 20 gallons daily per person), the challenge may not be in locating and drilling for water, but in finding who can identify water sources and give permission for using the sources.

In desert mountain areas, wells should be sited on the alluvial fans that extend from the mountains to the desert (see Figure 2-41). Mountain areas usually receive more rainfall, and the streams draining away from the mountains carry coarse gravels and sands that, when deposited, produce the fans (see Figure 2-42). At moderate depths, these fans may yield water. In deserts such as in Egypt, Jordan, and Saudi Arabia, deep confined aquifers are capable of producing extensive quantities of water. Locally, shallow confined aquifers come to the surface at an oasis, characterized by more extensive vegetation than the surrounding areas (see Figure 2-43). Wells may be sited in the vicinity of an oasis to tap a confined aquifer.

Qanats are good indicators of groundwater in some desert areas like Iran. A qanat is a man-made, gently inclined underground channel that allows groundwater to flow from alluvial gravels at the base of hills to dry lowlands (see Figure 2-44). In effect, qanats are horizontal wells. On aerial photographs, qanats appear as a series of ant-mound-like openings that run in a straight line and act as air shafts for the channel. They may be found in arid regions of Southwest Asia and North Africa. Qanats may be up to 30 kilometers in length.
Figure 2-42. Desert Mount and Plain Terrain

Figure 2-43. Oasis

Figure 2-44. Qanat System
2.9 WATER QUALITY

Most water is run through reverse osmosis water purification units (ROWPU's) or tactical water purification systems before it is used, so the effect of contamination is minimal. The list below describes different types of contamination in more detail:

1. **Aquifer Contamination.** Military engineers must be aware of possible aquifer contamination. As groundwater is transmitted from recharge to discharge areas, it contacts soils and rocks of the earth’s crust. Contact causes some dissolution of soil and rocks into the water and alters the chemistry of the groundwater. Discharge areas that appear to be good well sites because of shallow groundwater may have poor water quality and may be poor sites for groundwater development. Discharge areas often correspond to zones of poor water quality. Generally, the longer the distance between the recharge and discharge areas, the poorer the water quality at the discharge area. The water-quality reduction is from the contact between the groundwater and the aquifer material during flow. Water consumption by plants often results in decreased water quality by the concentration of soluble salts in the groundwater.

In very shallow groundwater (less than 10 ft below land surface), water quality can be decreased by direct evaporation of water from the soil. The use of vegetation type helps infer groundwater quality characteristics. Saltbush around playas indicates not only the presence of shallow groundwater but also the probable occurrence of saline water, which would require treatment. The high evaporation rate in arid environments concentrates chemicals in the water, resulting in brackish or saline water quality.

2. **Saltwater Intrusion.** Saltwater intrusion into fresh groundwater is a problem in coastal areas and on islands. Salt water is unfit for most human use and is harmful to automotive cooling systems, boilers, and other types of machinery. Chemical analysis determines the accuracy of contamination and salt levels. The average concentration of dissolved solids in sea water is about 35,000 parts per million (ppm) (3.5 percent). Most salts are chlorides.

Fresh water floats on salt water when salt water and fresh water are present in sediments. Contact between the two is determined by the head of the fresh water above sea level and by the relatively greater specific gravity of the salt water. The average specific gravity of sea water is about 1.025 (taking pure water as 1.000). For every foot of fresh water above sea level about 40 ft of fresh water is below sea level in homogeneous soils. The condition is best exhibited by small islands and peninsulas composed of permeable sands surrounded and underlain by salt water (see Figure 2-45). The head of fresh water and resistance of the pores in sand prevents salt water from entering the middle zone and mixing with fresh water. The diffusion zone (contact) between fresh water and salt water is narrow (less than 100 ft wide) unless affected by heavy pumping.

The amount of fresh water that is pumped without intrusion of salt water depends on local conditions, type of well, rate of pumping, and the rate of recharge by fresh water. Any decrease in the head of fresh water by pumping or decrease in rainfall raises the saltwater level (see Figure 2-46). The cone of depression (drawdown) produced in the freshwater level around a well allows a corresponding rise in the underlying salt water. Pumping a well should be restricted because salt water will enter the well if drawdown is maintained substantially below sea level for extended periods. The pumping rate should not exceed the rate of recharge. Saltwater intrusion is a potential problem when drilling in coastal-plain environments. Salt water may move into zones previously occupied by fresh water, this is called saltwater encroachment. The fresh water and the salt water migrate toward the well screen until a new balance between the waters is established (see Figure 2-47).

3. **Groundwater Contamination.** Possible aquifer contamination from human activities should be considered when evaluating potential supplies of groundwater. Waste products are sources of groundwater contamination in some areas. Sources of waste products include agricultural activities; domestic, municipal, and industrial waste disposal OPS; mine spoil piles and tailings; and animal feedlots.
Figure 2-45. Permeable Sands Surrounded by Salt Water

Figure 2-46. Pumping Effects in Salt Water

Figure 2-47. Saltwater Encroachment
Figure 2-48 shows how waste contamination enters the groundwater. Groundwater pollution occurs in both urban and rural areas and is affected by differences in chemical composition, biological and chemical reactions, density, and distance from discharge areas. Non waste pollutants include leaks from buried pipelines, highway deicing (salting), pesticide and herbicide applications, and accidental spills from surface transportation and manufacturing activities. Supplemental information on WRDB overlays often indicates the severity of man-induced pollution. Especially important are aspects of bacterial contamination that will preclude the use of the groundwater prevalent in many developing countries. Groundwater contamination may also occur from other wells into the same aquifer; requiring exercise control or coordination over aquifer access which is a challenge in water stressed regions. Well drillers should consider the proper location of water wells as shown in Figure 2-49.

Small wells often have shallow aquifer sources. It has been shown that sources a few feet below the surface can be reached by septic tanks, outhouses, and human waste.

Locate wells at higher elevations than potential contamination points.

Some minimum distances from potential biological pollution sources have suggested in Gibson’s Water Well Manual for sand filtration capacity soil. As a minimum, a well should not be located within: (1) 10 ft of a cast curb sewer or sewer lines; (2) 50 ft of a septic tank or tightly jointed tile sewer; (3) 75 ft of an earth pit or drain field; (4) 100 ft of a cesspool with raw sewage (although the United States (US) Public Health Service recommends at least 150 ft).

CHAPTER 3

Field Operations

3.1 TEAM CONCEPT

The list below describes the water-well drilling team concept and key positions:

1. **Leader/tool pusher/officer in charge (OIC)**. Well drilling teams deploy to the field to construct water wells. These teams normally deploy with the organic equipment they use to drill and complete the well. Teams are manned for continuous OPS and consist of two complete drilling crews, a mechanic, and a detachment leader. The detachment leader is usually responsible for:

   a. Training and caring of team members.

   b. Caring and maintaining of team’s organic equipment.

   c. Coordinating with the supporting engineer unit.

   d. Deploying the team.

   e. Laying out the drilling site.

   f. Developing safety guidelines for the well drilling team.

2. **Driller**. A drill team, which consists of a driller and two helpers, operates the drilling rig. A driller’s responsibilities include:

   a. Operating and controlling the drilling rig.

   b. Establishing (and modifying when necessary) the drilling rate.

   c. Monitoring mud mixture and sufficient volume.

   d. Monitoring the drill cuttings.

   e. Maintaining a driller’s log of the well.

   f. Preventing accidents around the drilling rig.

3. **Helper/derrick**. A helper is responsible for:

   a. Making drill rod connections.

   b. Ensuring an adequate mud mixture during drilling.

   c. Maintaining and caring for the rig, tender, and tools during the drilling operation.

4. **Worker/oiler/repairman/maintenance/mud man (WORMM)**. A WORMM is responsible for:
a. Conducting clean up of site, shovels pits, and keeps supplies handy.

b. Checking and lubricating the rig at prescribed intervals during shift.

c. Making small repairs to rig and support equipment onsite.

d. Coordinating all pre and post operator maintenance of all equipment.

e. Ensuring the mud program is good; adds products as directed by driller.

5. **Mechanic.** A mechanic is responsible for:

a. Performing repairs on the rig and auxiliary equipment.

b. Supporting the team where needed in support of drilling OPS.

### 3.2 TEAM PLANNING, COORDINATION, AND PREPARATION

A well-drilling team’s primary responsibility in planning and preparing for a drilling operation is to maintain a state of readiness. They must train, practice, and discuss OPS continuously. They should study information about specific sites and determine alternate solutions to potential problems. Periodically, teams should check each component of the well drilling equipment. Team members must maintain drilling rigs and tender trucks in good operating condition. Before leaving for the mission area, teams should inventory all tools, parts, drilling accessories, and supplies.

Planning requirements to support well drilling teams are similar to those needed for any augmentation team. Well drilling teams do not have an organic headquarters. Well drilling teams should be deployed and employed by an engineer unit capable of providing equipment, maintenance, administrative, and logistical support. Water wells are engineer construction projects and must be planned, researched, managed, inspected, and reported just as any other project. The unit that the well drilling team is attached to should provide the team with construction (field or tactical) standing operating procedures (SOPs). The team should report well drilling progress and procedures according to the SOP.

The well drilling project should be managed by the critical-path method (CPM). The well drilling team’s commander must coordinate and work closely with the construction or OPS officer of the supported unit to ensure timely researching and reporting. When well drilling teams complete the well drilling mission, they turn the well over to the OPS officer for disposition. The team then moves to the next project. The OPS Officer arranges transfer of the completed well, operating equipment, and technical specifications to a water-purification team, an installation, or a HN official.

Well drilling teams are in great demand in most OAs. Teams may not be able to return to a well site to perform repairs and keep up with the anticipated work load. The senior engineer of the supported unit has to set priorities for the team’s work schedule and should consider including the repair of existing and recently drilled wells in work estimates. The senior engineer must also determine if the teams have the skills or equipment needed to repair the wells before filing a request.

The unit’s OPS section, in coordination with the well drilling team, should prepare a construction estimate to determine the needed support for the well drilling operation. Team experience and land formations dictate the length of a well drilling operation. Staff personnel should consider the following when planning for the augmentation of a well drilling team:

1. Transportation of the well drilling team’s equipment and personnel by land, air, or sea, according to the unit movement books and operator manuals.

2. Reconnaissance and route selection to mission sites.
3. WDRT assistance and graphic products from the WRDB to select a potential drilling site.

4. Security during movement and drilling OPS.

5. Earth-moving assets to clear and level the drilling site and excavate mud pits.

6. Material handling equipment to offload well-completion kit materials, as needed.

7. Administrative support, including postal and legal services.

8. Logistical support, including all classes of supply and arrangements for mess; petroleum, oils, and lubricants (POL); maintenance; and medical support.

9. Delivery of the initial drilling water supply, if required.

10. Turnover of the completed well to a water-purification team, installation, or HN official.

11. Well-completion kit or component resupply.

12. Communications support.

13. Reporting procedures.


3.3 DEPLOYING TEAMS

Well drilling units are considered and organized as a specialized skill team. They are not self-sufficient. These teams depend on an engineer unit or a HHQ that is capable of providing support needed to accomplish the mission.

A well drilling team leader must ensure that the unit the team is attached to understands the mission and capabilities of the team. Because a well drilling team is small, there is little redundancy and no surplus labor. Therefore, the leader must request in advance any additional personnel needed to complete the mission. Since a well drilling team only has the equipment necessary to drill under optimum conditions the team leader must also request the following from the supported unit:

1. Transportation support of the equipment and personnel by land, air, or sea, according to the unit movement books and operator manuals.

2. Routes to the proposed drill site.

3. WDRT assistance and graphic products from the WRDB and an indication of where the OA commander wants the well.


5. Clearing and leveling of the drill site.

6. Excavation and maintenance of mud pits.

7. Off loading and transportation of well-completion materials.

8. Administrative support, including postal and legal.

9. Logistical support, including all classes of supply with special emphasis on repair parts.
10. Mess and potable water.
11. Fuel and POL products and continual resupply.
12. Specialized maintenance, evacuation, and on-site welding support.
13. Medical support, including medical evacuation (MEDEVAC) procedures.
14. Initial water supply and resupply.
15. Timely delivery of pea gravel for gravel packing material.
16. Arrangements to turn over the completed well to the supported unit OPS cell.
17. Communications support.
18. Reporting procedures.
20. Plans for the next mission.

3.4 SITE PREPARATION

Most sites require some preparation before setting up the drill rig. In rugged terrain, teams may have to excavate into a hillside requiring the preparation of a drilling platform. The drilling platform (or drilling area) should be large enough so teams can safely operate each component during the drilling operation.

Where excavation is not expedient, teams may have to construct mat or timber platforms to level the rig. Teams must consider locations for the rig and mud-pit, working areas, and well-completion components and accessories; location for and access to drill pipe racks; and location and maneuverability of the tender truck during the preparation phase. If a mud pit is needed and the drill rig does not have a portable mud pit or if the portable pit does not have sufficient volume, teams should construct a pit during the site-preparation phase.

Refer to Service-specific appendices and drill rig operator’s manuals for drill rig set up.

CAUTION

Teams shall always place the drill rig on stable, level ground and clear the site of obstacles as well as any potentially combustible materials. Avoid setting the rig up on a fill area since the rig could overturn.
WARNING

Check for overhead and underground power lines before moving the rig on site. Consider all power lines as being energized. Do not raise the mast around electrical wires without a ground guide. If power lines are a problem, teams must move the rig or make provisions for removal of the power lines.

Check the clearances listed below:

- If the power lines have a voltage of less than 50 kilovolts (kv), place the rig at least 10 ft from the power lines.

- If the power lines have a voltage of more than 50 kv, place the rig 10 ft plus 0.4 ft for every kv over 50 kv from the power lines.

Note

Historically, groundwater coming from its natural environment is considered of good sanitary quality. Because of this, personnel must understand the effects well drilling may have on the surrounding environment. Layers of rock and different formations protect the groundwater supply from contamination. Drilling a hole through these protective layers provides an access for bacteria and chemicals that could degrade water quality. Well drillers must take precautions to ensure they will not contaminate the well and the aquifer.

3.5 DRILLING FLUID

If using a rotary drill with mud, connect or place the suction line of the mud pump in the mud pit and fill the pit with water. When complete, close the standpipe valve and prime the mud pump. Mix the drilling fluid in the mud pit by slowly circulating fluid through the mud pump and adding drilling mud to the mixing hopper (see Figure 3-1). The drilling fluids usually used for mixing mud are a Wyoming-type bentonite drilling additive (Quick-Jel) or an organic or inorganic polymer fluid (Revert or E-Z Mud). Mix the additives until the desired weight and viscosity are reached for the drilling mud. Refer to Chapter 5 for additional details on mud mixing.

Figure 3-1. Mud Hopper
3.6 WELL DRILLING OPS

Before starting to drill, an appropriate drill bit must be selected. Consideration of the well diameter and the type of formations to be encountered are paramount. The types of bits are:

1. Drag bits. Use these bits for soil, unconsolidated materials usually found near the surface.

2. Tricone roller-rock bits. Use these bits for a variety of materials from soft formations through hard rock (see Figure 3-2). These bits are available in different degrees of hardness. Bits used for softer formations have longer teeth on the roller cones.

3. Down hole hammer bits. Use in consolidated, very hard material. Requires air compressor to operate.

The list below describes drilling OPS in more detail:

1. **Starting the Operation.** The first operation is spudding in (starting the borehole). Before starting to drill the actual hole, consider drilling a 6 to 7-1/2-inch test hole. Doing so will ensure that the larger hole is straight which should help locate the aquifer quicker. Use the following steps to start the drilling operation:
   
   - Step 1. Make up the drill bit on the collar and lower the bit to the ground.
   
   - Step 2. When the bit contacts the ground, start rotation and begin to drill.
   
   - Step 3. After the borehole advances 6 to 12-inches, engage the mud pump to start circulating the drilling fluid (which will be mud or air).
   
   - Step 4. After drilling down the collar, stop the rotation and raise the collar about 4-inches off the bottom of the borehole. Circulate the drilling fluid until all drill cuttings are removed.

2. **Finishing the Operation.** As a section of the drill string is completed, lift the bit 4 to 6-inches off the bottom of the hole to allow the cuttings to be removed by the mud pump. Once all cuttings are removed, add additional collars and drill rods until desired depth is achieved.

![Figure 3-2. Tricone Type Drill Bit](image)
3.7 SAMPLING AND LOGGING

Samples shall be recorded for every well drilled. During the drill operation, it is important to take samples of the cuttings in the drilling fluid (see Figure 3-3). Record the samples in a driller’s log according to basic classifications (sand, clay, or granite) and describe their color and consistency (coarse or free) when possible. Also, record the approximate depth of the sample. If samples are needed from a specific depth, stop the drilling operation and let the drilling fluid circulate until the cuttings reach the surface.

Other information that must be recorded is advance rate, reaction of the drill rig, any loss of circulation, and changes in drilling fluid consistency. Periodically, check the drilling fluid for viscosity, weight, and sand content. Log the test results and any adjustments made.

Finally, if the drill rig breaks down or needs repair or maintenance, record the information in the log. The information in the driller’s log can provide insight into local conditions, help determine well-screen locations, and plan for additional or future well installations.

Note

Always place the screen sections into the aquifer and not at the bottom of the hole.

3.8 CASING AND WELL SCREEN

Depending on the construction method, set the well casing in the well before or at the same time as the well screen. If the borehole has a tendency to cave in during drilling, install surface casing while drilling, but before reaching the desired depth (use this procedure when drilling in loose, unconsolidated materials). When installing the casing before the well screen, such as surface casing, the casing must be larger than the screen. Therefore, use a larger drill bit than the one used to complete the screen portion of the borehole. The decision to use surface casing should be made before mobilizing and should be based on the geologic information about the site. It is important to draw a diagram or working sketch of the well before setting the casing and screens; this practice will ensure optimum water collection due to proper screen placement. The list below describes surface casing, screening, and filtering and backfilling in more detail:

Figure 3-3. Taking Samples
1. *Surface Casing.* Use the following steps to install the surface casing:

- **Step 1.** Drill the borehole to a predetermined depth and remove all the cuttings by circulating the drilling fluid. Withdraw the drill string and remove the bit.

- **Step 2.** Connect the elevators to the first section of surface casing that is lifted over the borehole by using a casing elevator and the hoist (see Figure 3-4).

- **Step 3.** Lower the casing into the well and set the slips (see Figure 3-5), which suspend the casing in the well, in the spider base (see Figure 3-6).

- **Step 4.** Disconnect the elevator, hoist the next casing section with the elevator, place it in the first section, and join the two sections. Lift the string of casing slightly, remove the elevator from the lower section, lower the casing, and repeat the process until the last casing section is suspended in the well.

- **Step 5.** Grout the casing in place with a cement grout. After the grout sets (about 24 hours), resume drilling OPS using a drill bit that will fit inside the surface casing. Drill the well to the desired depth, case, and screen the lower section of the well, using the single-string method.

![Figure 3-4. Connecting an Elevator to a Casing](image)

![Figure 3-5. Setting Slips](image)
Figure 3-6. Casing in a Spider Base

2. **Screening.** Use the following method to install screens:

- Step 1. Place a casing section in the well. Cap the casing on the lower end so materials from the bottom of the well will not enter the well.

- Step 2. Suspend a screen section over the well and attach the screen section to the casing section.

- Step 3. Lower the screen and casing section. Suspend them in the well either by the elevator resting on the rotary table or by slips in the spider bowl.

- Step 4. Add casing until the screen reaches the desired depth. Refer to Chapter 4 for details on other screening methods.

3. **Filtering and Backfilling.** The last procedure when installing screen and casing is to place a gravel-pack filter around the screen and backfill material around the casing. If the screen is placed in material such as gravel or very coarse sand, gravel pack may not be needed. Place the gravel filter material around the outside of the casing and deposit the material to the bottom of the well. Add gravel to about 5 ft from the top of the screen (use the sounding method to determine the level of the gravel). Add impervious backfill around the casing from the gravel pack to about 10 to 20 ft from the surface. If grout is used instead of impervious material, add a couple of ft of clay above the gravel to prevent the grout from entering the gravel filter and bring the grout to the surface.

**3.9 WELL DEVELOPMENT**

Frequently, when a well is first installed, the efficiency (production per foot of drawdown) is not satisfactory, requiring the development of the well by pumping, surging, or both. Developing a well removes the remaining drilling fluid, breaks down any filter cake buildup on the borehole wall, and flushes the fines in the formation (adjacent to the gravel pack) into the well. Make sure that the well is pumped of all fine sediments and sand with an airlift before installing a submersible pump or the pump and components will wear out prematurely. Additionally, pump or blow the drilling fluid out of the well and agitate the water in the well to produce an alternating in and out flow through the well screen (or gravel pack). Although there are several methods available to develop a well the simplest method follows:

- Step 1. Attach a weighted plunger or surge block to the sand line. Lower the surge block into the well below the water level, but above the screen.
• Step 2. Lift the block and then drop the block 3 to 4 ft, repeatedly, to surge the well. Continue this action for several minutes.

• Step 3. Remove the surge block and lower a bailer into the well. All of the sand that was pulled into the well is bailed from the sand trap.

• Step 4. Repeat the process, noting the amount of sand brought into the well each time. Development is complete when 5 milligrams or less of sand per liter of sampled water is removed.

• Step 5. Sanitize the well with calcium hypochlorite.

3.10 SANITARY SEALS

All wells must have a sanitary seal to prevent contamination from surface runoff. Mix cement grout and place it in the annulus between the well casing and the borehole wall. Next, extend the grout from the surface to the top of the backfill material (30-foot minimum). A concrete platform (about 4 ft by 4 ft) should also be poured around the casing at the surface with the casing extended at least 1 foot above the surface. The upper surface of the slab and the surrounding area should be gently sloping away from the well for better drainage. In addition to a surface grouting, a well seal (a type of bushing or packing gland) shall be installed to prevent foreign materials from entering the inside of the well casing. Normally the well seal is installed with the pump, which is after all development, testing, and disinfection.

3.11 PUMPING TESTS

After installing a well, a pumping test must be performed. The gpm, footage of drawdown, and available drawdown give an immediate indication of the well’s capacity and whether the well can produce the required amount of water. If the well is considered permanent, the pumping test should help evaluate any future performance deterioration. A throttle or a valve on the pump should be installed to regulate water extraction and prevent pump damage if the pump from the well-completion kit is capable of producing more water than the well.

Before starting the test, place a sounding device, such as an M-Scope, in the well to measure the water level during the test. The flow rate must also be measured and regulated during the test. The most proficient way to measure the flow rate is with a flow meter. However, a calibrated container and a stop watch may also be used. Use the following procedures to perform the pumping test:

• Step 1. Temporarily install a pump in the well below the anticipated drawdown depth, but above the screen.

• Step 2. Measure the static water level and start the pump. During the test, one team member should monitor the flow rate and try to keep the flow rate constant.

• Step 3. Record the drawdown with the flow rate. Take early readings quickly; then spread out the readings as testing progresses. An ideal reading schedule would be the initial reading and then a reading at 30 seconds, 1 minute, 2 minutes, 4 minutes, 8 minutes, 15 minutes, 30 minutes, 1 hour, 2 hours, and so forth. It is important to record the exact times that readings of the drawdown and flow-rate measurements are taken. The length of a test usually depends on the purpose of the well, the urgency for water, and the time available. On small water supplies, an adequate evaluation takes 4 to 5 hours. For large, permanent supplies, tests could take from days to weeks.

• Step 4. Set and adjust the pump. The well is now ready for use or for connecting to a treatment, storage, and distributions system.
CHAPTER 4
Well Drilling Methods

4.1 MUD ROTARY DRILLING

Rotary drilling with mud is the most widely used method for water-well construction. A rotary drill rig has three functions: rotating the drill string, hoisting the drill string, and circulating the drilling fluid. A bit is rotated against the formation while mud is pumped down the drill pipe, through ports in the bit, and back to the ground surface through the annulus between the drill pipe and the borehole wall. Figure 4-1 shows the relative performance of drilling methods in various geologic formations. Drill cuttings rise to the ground surface in the drilling fluid. Rotary drilling is sometimes called mud rotary drilling. Drill pipes or rods are joined to a bit to form the drill string. The drill pipe is the link transmitting torque from the rig to the bit and carries the drilling fluid down the hole. The list below describes rotary drilling in more detail:

1. **Rotary Rigs.** Rotary rigs vary in design. Drilling rigs are truck-or trailer-mounted and are powered by an on-board engine or by a power takeoff (PTO) from the truck transmission. Power is delivered to the various components through hydraulic pumps and motors or through mechanical transmissions and clutches and geared on roller-chain drives. Many drill rigs may use both mechanical and hydraulic drives. Torque is applied to the drill string, which rotates by using three basic designs—rotary table, top head, and quill-and-drive bar. Military drilling machines use rotary tophead drives.

   a. **Rotary Table.** The rotary table is a rotating platform that transmits torque to the drill rod through the kelly. The kelly, which is attached to the mud swivel, is the uppermost section of the drill string that passes through the rotary table. The drill string may be square, hexagonal, or round with grooves or flukes on the outside wall. The drive kelly bar slides through the rotary table while rotating. By removing the kelly bar, drill pipe can be added and worked through the open hole in the rotary table. The rotary table normally is a mechanical, positive drive mechanism.

   b. **Top Head.** The top-head drive uses a power swivel. Torque is applied at the top of the drill string. The top-head mechanism moves down along the rig mast as the boring is advanced and is raised to the top of the mast to add a length of drill pipe. Top-head-drive drill rigs do not use a kelly bar. Most top-head drives are powered by hydraulic motors capable of variable speeds rather than positive constant rotation.

   c. **Pulldown.** Rotary rigs are equipped with a mechanism to apply a downward thrust to the drill string. This mechanism is called a pulldown or feed drive.

      Generally, two roller chains apply the thrust for rotary tables. The chains are attached to the kelly swivel and extended over sprockets at the top of the mast and under the rotary table. On older rigs, the sprockets under the rotary table are powered mechanically through a PTO and clutch. The pulldown chains on modern drill rigs are powered by a hydraulic motor, which provides better thrust control.

      The thrust mechanism on most top-head rigs consists of a pair of roller chains in two chain sections. One end of each section is attached to the swivel at the top of the kelly bar. The other ends are dead-headed to the top and bottom of the mast. Sprockets at the top and bottom of the mast act as idlers. Chains are powered in either direction by hydraulic rams. These rams apply thrust and are used in a hold-back mode to reduce the bit load of the weight due to the drill string. This chain mechanism is also the main hoist for lifting the drill string.
### Figure 4-1. Relative Performance of Drilling Methods in Various Types of Geological Formations

<table>
<thead>
<tr>
<th>Type of Formation</th>
<th>Direct Rotary (with fluids)</th>
<th>Direct Rotary (with air)</th>
<th>Direct Rotary (down-the-hole air hammer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dune sand</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loose sand and gravel</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quicksand</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loose boulders in alluvial fans or glacial drift</td>
<td>2–1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay and silt</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Firm shale</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sticky shale</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brittle shale</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandstone—poorly cemented</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandstone—well cemented</td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Chert nodules</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Limestone with chert nodules</td>
<td>3</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Limestone with small cracks or fractures</td>
<td>3</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Limestone, cavernous</td>
<td>3–1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Dolomite</td>
<td>5</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Basalts, thin layers in sedimentary rocks</td>
<td>3</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Basalts—thick layers</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Basalts—highly fractured (lost circulation zones)</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Metamorphic rocks</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Granite</td>
<td>3</td>
<td>5</td>
<td>5</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

---

d. **Mud Pump.** A mud pump (see Figure 4-2) on a rotary drill is usually a positive-displacement, double-acting piston pump with capacities ranging from one to several hundred gpm at pressures up to several hundred pounds per square inch (psi). Power may be provided through a mechanical PTO and clutch, with or without a separate transmission. Power may also be provided by a separate engine or a hydraulic or air motor. Other types of pumps are used successfully, but their limited pressure capacity may jeopardize the success of the drilling operation (i.e., pump capacity (volume and pressure) can limit the effective depth of a drilling operation). The horsepower required to drive a mud pump often exceeds the power required to hoist and rotate the drill string.

c. **Hoists.** Man drill-head hoists (draw works) are mechanically or hydraulically driven wire-line winches. On top-head rigs, the pulldown chains are used as the main hoist. Many drill rigs have auxiliary hoists for handling pipe, bailing, and for other equipment. The bailing drum usually has less lifting capacity and a faster spooling rate than hoisting drums. Bailing drums can spool several hundred ft of wire line, which is sufficient to reach the bottom of most wells. Auxiliary hoists may be powered mechanically or hydraulically.
2. **Drill Bits.** Figure 4-3 illustrates rotating speeds for all sizes and types of bits in various formations. Figure 4-4 is a guide for bit selection.

   a. **Tricone Roller Bits.** These bits are best suited for brittle or friable materials. The tricone bit consists of three cone-shaped rollers with steel teeth milled into the surfaces. Tooth locations are designed so that as the cone rotates, each tooth strikes the bottom of the hole at a different location. Drilling fluid is jetted on each roller to clean and cool it. The cutting action is a progressive crushing under the point load of each tooth. Roller bits designed for rock, rocky soil (gravel), and soft formations (shale) have long teeth. The bits for harder formations have smaller, stronger teeth. The gauge teeth on bits designed for very hard rock are reinforced with webs. For extremely hard formations, milled teeth are replaced with connected carbide buttons.

   b. **Drag Bits.** These bits are used in soil and other unconsolidated materials. The blades are designed so that they cut into the formation with a carving or scraping action. Drag bits may have multi-blade, hardened-steel, finger-shaped teeth or may have connected carbide-reinforced cutting edges.

![Figure 4-2. Mud Pump](Image)

**WARNING**

Remove all jewelry and loose clothing before starting rotary drilling OPS.

3. **Rotary Operation.** Standard rotary drilling involves the bit rotating against the formation. Drilling fluid is pumped through the drill string and face of the drill bit and backup the annulus to the surface. The rotary action of the bit loosens the material, while the drilling fluid cools and lubricates the drill pipe and bit and carries cuttings to the surface. The drilling fluid is under high hydrostatic pressure and supports the wall of the borehole against caving. The properties of the drilling fluid are important to the drilling operation. Well drillers must have knowledge of drilling fluids and their use for successful rotary drilling. Drillers must also know about drilling-fluid additives used to prevent problems in drilling. Preventing drilling problems, such as an unstable borehole wall or a stuck tool, is easier than fixing the problem after it occurs. Refer to Paragraph 4.1, item 5 for additional details on drilling fluids. Before drilling with mud, build either a portable or an excavated mud pit. The decision depends on the hole depth and the alternatives available. Refer to Paragraph 4.1, item 5 for additional details on mud pits.
### Bit Sizes and Types

<table>
<thead>
<tr>
<th>Bit Sizes and Types</th>
<th>Sticky Shales or Gumbos</th>
<th>Soft Unconsolidated Shales, Silts, Sandy Shales, etc.</th>
<th>Medium Hard Shales, Sandy Shales, Soft Chalk</th>
<th>Medium Hard Sandstones, Hard Very Sandy Shale</th>
<th>Very Hard Sandstones, Quartzite, Angular Limestones, Anhydrite</th>
<th>Hard Brittle Shale and Limestone Conchoidal Fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 to 20 inch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drag</td>
<td>100–130</td>
<td>100–130</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zublin</td>
<td>100–160</td>
<td>100–150</td>
<td>100–175</td>
<td>125–175</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock (rolling cutter)</td>
<td>125–200</td>
<td>100–200</td>
<td>60–125</td>
<td>40–60</td>
<td>40–150</td>
<td></td>
</tr>
<tr>
<td>10 to 13 inch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Drag</td>
<td>100–175</td>
<td>100–300</td>
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</tr>
<tr>
<td>Disc</td>
<td>110–180</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock (rolling cutter)</td>
<td>150–300</td>
<td>100–250</td>
<td>80–120</td>
<td>40–80</td>
<td>60–150</td>
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<td>6 to 10 inch</td>
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<tr>
<td>Drag</td>
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<td>100–200</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zublin</td>
<td>150–200</td>
<td>100–150</td>
<td>150–225</td>
<td>150–200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock (rolling cutter)</td>
<td>150–300</td>
<td>100–250</td>
<td>80–125</td>
<td>40–100</td>
<td>60–200</td>
<td></td>
</tr>
</tbody>
</table>

The minimum speeds given are for flat lying strata and certain type bits. The maximum speeds are for flat or inclined formations. The maximum allowable weight may be carried in flat beds and the minimum in steeply dipping strata. Slower and faster speeds than these recommended are useful in specific and more or less unusual cases. (Brantly, 1961)

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**Figure 4-3. Recommended Rotating Speed for Bits (in rpm)**

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**Figure 4-4. Guide for Bit Selection**
4. **Variables.** Bit design, weight on bit, rotation speed, fluid consistency, cumulation pressure, and velocity affect rotary drilling. Since experience helps drillers handle unique problems and conditions, experimentation may help develop the best drilling procedure. Before starting the hole, plumb the kelly to provide a straight hole (see Figure 4-5). The rig may be out of level as long as the kelly is straight.

a. **Bit Design.** Rotary drill bits are designed to cut specific material types. Choose the drill bit based on the anticipated formation. Either drag or rotary bits may be available at a drill site. Normally, a drag bit is used to begin a borehole in unconsolidated overburden materials. These bits are used for hard, medium, and soft rock and are part of the drilling-rig equipment. When drilling in soft rock, use a medium soft-rock drill bit. In very hard rock, stop mud rotary drilling; install casing to the rock layers, and use a down-hole air hammer. The objective is to produce a hole quickly and efficiently, but care must be taken to not penetrate too quickly. Serious problems such as the drill string sticking in the hole, excessive completion delays, equipment damage, and loss of the hole may occur by producing cuttings faster than that removed.

b. **Weight on Bit.** Adding weight on the bit increases the torque required for rotation. Too much weight can cause excessive penetration and produce cuttings that are too large and heavy. Large cuttings are difficult to wash out and may cause gumming and premature failure of the bit. Insufficient weight reduces or stops penetration and can produce fine cuttings. In cohesive soils, fine cuttings may thicken the drilling fluid and fail to settle in the mud pit. How weight is applied can also cause serious alignment problems and difficulty in well construction. Rotary-drilled boreholes spiral slightly and are seldom straight. Once spindling occurs, weight added by pulling down with the drill rig bends the string and magnifies the deviation. As such, the chain pulldown should never be used to advance the hole beyond the first run (20 ft). Ideally, the drill string should be kept in tension by adding drill collars (heavy wall drill steel) at the bottom just above the bit. Figure 4-6 provides drill collar weights.

Figure 4-5. Plumbing the Kelly
<table>
<thead>
<tr>
<th>Collar OD (in)</th>
<th>Bore of Collar (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 1/2</td>
</tr>
<tr>
<td>3 1/8</td>
<td>24.4</td>
</tr>
<tr>
<td>3 1/2</td>
<td>26.7</td>
</tr>
<tr>
<td>3 3/4</td>
<td>31.5</td>
</tr>
<tr>
<td>3 7/8</td>
<td>34.0</td>
</tr>
<tr>
<td>4</td>
<td>35.7</td>
</tr>
<tr>
<td>4 1/4</td>
<td>39.4</td>
</tr>
<tr>
<td>4 1/2</td>
<td>42.2</td>
</tr>
<tr>
<td>4 3/4</td>
<td>48.0</td>
</tr>
<tr>
<td></td>
<td>54.2</td>
</tr>
<tr>
<td>5</td>
<td>60.1</td>
</tr>
<tr>
<td>5 1/4</td>
<td>67.5</td>
</tr>
<tr>
<td>5 1/2</td>
<td>74.7</td>
</tr>
<tr>
<td>5 3/4</td>
<td>82.1</td>
</tr>
<tr>
<td>6</td>
<td>89.9</td>
</tr>
<tr>
<td>6 1/4</td>
<td>98.1</td>
</tr>
<tr>
<td>6 1/2</td>
<td>106.6</td>
</tr>
<tr>
<td>6 3/4</td>
<td>115.5</td>
</tr>
<tr>
<td>7</td>
<td>124.6</td>
</tr>
<tr>
<td>7 1/4</td>
<td>134.1</td>
</tr>
<tr>
<td>7 1/2</td>
<td>143.9</td>
</tr>
<tr>
<td>7 3/4</td>
<td>154.1</td>
</tr>
<tr>
<td>8</td>
<td>164.6</td>
</tr>
<tr>
<td>8 1/4</td>
<td>175.4</td>
</tr>
<tr>
<td>8 1/2</td>
<td>186.6</td>
</tr>
<tr>
<td>8 3/4</td>
<td>198.1</td>
</tr>
<tr>
<td>9</td>
<td>207.8</td>
</tr>
<tr>
<td>9 1/2</td>
<td>232.4</td>
</tr>
<tr>
<td>10</td>
<td>255.9</td>
</tr>
<tr>
<td>10 1/2</td>
<td>283.3</td>
</tr>
<tr>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

(Joy, 1978)

Figure 4-6. Drill-Collar Weights (lb)

CAUTION

Use the pulldown feature on the drill rig as a last resort for short distances in hard strata.
Bit weight required to cut rock depends on the design of the bit and the strength of the rock. Roller bits need a minimum of 2,000 psi of bit diameter for soft rock and shale and a maximum of 6,000 psi of bit diameter for hard rock. Before drilling, add drill collars instead of drill pipe until the load is sufficient for reasonable cutting. The drill string may have to be held back in order to add drill pipe as digging proceeds. Figure 4-7 provides weight on bit and rotary speed recommendations.

c. **Drill Steel.** Drill rods, collars, stabilize, subs, and bits are available in different sizes and materials. In most drilling systems, drill rods are either steel or aluminum and come in lengths of either 5 or 20 ft.

d. **Rotation Speed.** Rotation speed is determined by the weight on the bit and the material being drilled. The speed must be regulated to produce the correct size cuttings, which is derived from experience.

e. **Fluid Requirements.** Fluid requirements depend on size, weight, nature of cuttings, and circulation velocity. Velocity depends on capacity and condition of the mud pump, annular area in the borehole, and the stability and permeability of the formation. Refer to Paragraph 5 for additional details on drilling fluids. Use the following formula and Figure 4-8 to determine the time required to evacuate cuttings from the borehole.

\[
Q = \frac{gpm \text{ of pump} \times 24.5}{AS}
\]

\[
AS = \pi D^2 - \pi d^2
\]

\[
T = \frac{Q}{HD}
\]

where:

- \(Q\) = uphole velocity, in feet per minute (fpm)
- \(AS\) = annular space, in square inches
- \(D\) = bore hole diameter, in inches
- \(d\) = drill string collar diameter, in inches
- \(HD\) = hole depth, in feet
- \(T\) = evacuation time, in minutes

<table>
<thead>
<tr>
<th>Bit Classification</th>
<th>Weight per in/cm of Bit Diameter</th>
<th>Rotary Speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lb/in</td>
<td>kg/cm</td>
</tr>
<tr>
<td>Soft formation</td>
<td>3,400 to 6,750</td>
<td>609 to 1,210</td>
</tr>
<tr>
<td></td>
<td>4,050 to 7,800</td>
<td>725 to 1,400</td>
</tr>
<tr>
<td>Medium formation</td>
<td>4,500 to 9,000</td>
<td>806 to 1,610</td>
</tr>
<tr>
<td>Hard milled tooth bit</td>
<td>5,600 to 11,250</td>
<td>1,000 to 2,010</td>
</tr>
<tr>
<td>Hard insert bit</td>
<td>2,250 to 5,600</td>
<td>403 to 1,000</td>
</tr>
<tr>
<td></td>
<td>4,500 to 9,000</td>
<td>806 to 1,610</td>
</tr>
<tr>
<td>Hard friction bearing bit</td>
<td>4,500 to 6,750</td>
<td>806 to 1,210</td>
</tr>
</tbody>
</table>

(*Ingersoll-Rand*)

Figure 4-7. Weight on Bit and Rotary Speed
f. Circulation Pressure and Velocity. These elements of the drilling fluid are controlled by the pump capacity and speed. The fluid’s density, velocity, and viscosity let it carry cuttings. If the drilling fluid is too thick, cuttings will not settle in the mud pit. Sufficient velocity with a fluid of low viscosity (even water) carries drill cuttings to the surface. Excessive velocity erodes the wall of the hole to the extent of failure.

Pump pressure results from flow resistance caused by viscosity, friction, weight of the fluid column, or restrictions in the circulating system. Pressure should be exerted at the ports in the bit, causing a downward jetting as the fluid exits. Regulate mud-pump pressure by varying the revolutions per minute (rpm) of the pump. Mud-pump pressure against the bit is not harmful if it does not exceed the operating pressure of the pump. Other sources of fluid pressure can be detrimental. Pressure from friction occurs if the drill string is long for its inside diameter (ID) or pipes are internally upset. Frictional pressure increases wear in the pump. Pressure from the weight of the fluid column in the annulus or from a restriction in the annulus caused by an accumulation of cuttings indicates insufficient cleaning. This type of pressure can cause formation damage, resulting in lost circulation and wall damage.

g. Stabilizers. Unless the drill string includes stabilizers (see Figure 4-9) for large drill bits, drill a pilot hole, using drill collars as stabilizers. The initial pilot hole (6-to 7 1/8-inch diameter) will be straighter and easier to sample. The location of aquifers will also be easier to determine. Use a larger bit to ream the hole to the desired size. Use overreaming bits, if available, because they follow the pilot hole best.

5. Drilling Fluids. Drilling fluid is circulated in rotary drilling to cool, clean, and lubricate the drill string, to flush cuttings from the hole, and to stabilize the borehole wall. Water is the basic fluid and is satisfactory for lubricating and cooling the tools. However, water has limited abilities to carry cuttings and stabilize the borehole wall. Many drilling fluid additives are prepared and formulated for various purposes. Polymer fluids and water-based clay fluids (muds) are the primary additives used in water-well drilling. Figure 4-10 lists drilling fluids.
Mud cools and lubricates through heat absorption from the bit and reduction of drill-string abrasion against the borehole wall. Heat is generated as the bit scrapes and grinds. Without the cooling fluid, the bit would overheat and be useless. Research indicates that removing the cuttings around and under the bit is the most important factor in keeping the bit cool. Requirements for cooling fluid are less than those for removing the cuttings.

Therefore, by keeping the borehole clean with the fluid while drilling the bit is also cooled and lubricated. This is true with clay muds and polymer fluids. Clay muds are colloidal suspensions. Solutions are chemical mixtures that cannot be separated by simple filtering. Suspensions are physical mixtures of solids and liquid that may separate during filtering. This distinction underlies the difference in behavior between drilling polymers (solutions) and drilling muds (suspensions). Natural clays can also be mixed with water for use as a drilling mud since its properties are marginal for good water-well drilling.

Hydrostatic pressure allows the fluid to support the borehole wall and is a function of the density or weight of the mud column. Important characteristics of a drilling mud are viscosity and weight to carry cuttings, gel strength, yield point, and active clay solids for filter cake. Use the following formula to calculate hydrostatic pressure:

\[ H_p = (Md)(d)(0.052) \]

where:

\[ H_p = \text{hydrostatic pressure, in psi.} \]
\[ Md = \text{mud density, in lb per gallon.} \]
\[ d = \text{hole depth, in ft} \]

For example, the hydrostatic pressure of a 200-foot hole with a mud weight of 9 lbs is as follows: 9 ft x 200 ft x 0.052 = 93.6 psi.
a. **Polymers.** Polymer fluids are water-based and very low in solids. Polymer admixtures are organic, inorganic, natural, synthetic, or synthetically formulated natural polymers. Polymer additives are formulated for various drilling-fluid purposes and are used alone or to enhance clay muds. Polymers, containing salt and other contaminants, are available and are compatible with water. Polymers are more sensitive to pH than are bentonite muds. Change the pH to effect desirable changes in the polymer fluid. Drilling-fluid weight impacts drilling rate and high-density drilling fluid reduces drilling rate. There is strong indication that the solids of a fluid have a similar effect as density. Polymer fluids are very different from clay muds because a large part of the polymer is soluble in water and becomes a solution when mixed with water. Long, complicated molecular chains tie up the water and can build viscosity without solids. In water-well drilling, many polymers are manufactured for producing drilling fluids, such as E-Z Mud, Revert, and Poly-Sal. E-Z Mud is a synthetic, inorganic polymer. Revert is a natural, organic polymer fluid derived from a guar plant.

Polymers are generally best mixed through a mud gun. Polymers used for special purposes are available from the manufacturer complete with specifics on how to use the product. Most polymers can hydrate more water than a high-grade bentonite. Up to ten times more bentonite is needed to build the same viscosity in a given amount of fluid, depending on the quality of the polymer. A polymer does not fully hydrate as quickly as bentonite. Mix the polymer very slowly through the mud gun a minimum of four hours before using for more complete hydration. The fluid will thicken as hydration continues, so do not mix to the desired viscosity. Some polymers possess physical qualities that can result in unusual

---

### Figure 4-10. Drilling Fluids

<table>
<thead>
<tr>
<th>Description</th>
<th>Baroid</th>
<th>Primary Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bentonite</td>
<td>Aqualgel</td>
<td>Viscosity and filtration control in water-based drilling fluids</td>
</tr>
<tr>
<td>Sub-bentonite</td>
<td>Baroco</td>
<td>For use when larger particle size is desired for viscosity and filtration control</td>
</tr>
<tr>
<td>Attapulgite</td>
<td>Zeogel</td>
<td>Viscosifier in saltwater drilling fluids</td>
</tr>
<tr>
<td>Beneficiated bentonite</td>
<td>Quik-Gel</td>
<td>Quick viscosity in fresh water with minimum chemical treatment</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Polymers</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural organic polymer</td>
<td></td>
<td>Lightweight, low-solids drilling fluid for viscosity and filtration control in water-based drilling fluids</td>
</tr>
<tr>
<td>Synthetic organic polymer</td>
<td>E-Z Mud</td>
<td>Lightweight, low-solids drilling fluid for viscosity and filtration control in water-based drilling fluids made with bentonitic additives</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Foaming Agents</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Foaming agents</td>
<td>Quik-Foam</td>
<td>Used in air drilling to increase hole-cleaning capability and reduce compressor requirements for a given depth or rate of water inflow</td>
</tr>
<tr>
<td>Sodium triopolyphosphate (Na₃P₃O₁₀)</td>
<td>Barafos</td>
<td>Thinner for freshwater drilling fluids with clay additives</td>
</tr>
<tr>
<td>Sodium acid pyrophosphate (Na₂H₂P₂O₇)</td>
<td>SAPP</td>
<td>For treating cement contamination in drilling fluids made with clay additives*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detergents</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Detergent</td>
<td>CON DET</td>
<td>Used in water-based drilling fluids made with clay additives to aid in dropping sand; a detergent reduces torque and minimizes bit balling.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bactericides</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraformaldehyde</td>
<td>Aldacide</td>
<td>Prevents organic additives from degradation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Commercial Chemicals</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium hydroxide (NaOH)</td>
<td>Caustic soda</td>
<td>For pH control in water-based drilling fluids</td>
</tr>
<tr>
<td>Sodium chloride (NaCl)</td>
<td>Salt</td>
<td>For solution weighting of water-based drilling fluids made with polymeric additives</td>
</tr>
<tr>
<td>Calcium chloride (CaCl₂)</td>
<td>Salt</td>
<td>For solution weighting of water-based drilling fluids made with polymeric additives</td>
</tr>
</tbody>
</table>

*Also used for development of wells drilled with bentonite additives.
hydration, gelling, and viscosity. Follow the manufacturer’s recommendations for hydration. Factors that affect the viscosity are quality of polymer, concentration and size of colloid, metallic ions in mixing water, temperature, rate of shear, and pH.

Water is the primary building block for drilling fluids. Water quality affects the overall performance of drilling fluids. The action of bentonite in water is seriously impaired by dissolved acids or salty substances. Acidic water usually contains dissolved metals that cannot be used unless treated. Hard water affects the suspending and sealing qualities of bentonite. The pH level is tested by using paper pH strips. The pH level should be 8 to 9. If the water is too acidic, treat it with soda ash at a ratio of 1 to 5 lbs of soda ash per 100 gallons of water. Following treatment, retest the pH level as before.

Do not use water from wetlands, swamps, or small ponds for mixing drilling fluids because the water may be contaminated. If these locations are the only source available, chlorinate the water before making the drilling fluid. Be careful because chlorine removes metallic ions that are necessary for viscosity in polymers. Adjust the pH of drilling water to 8.5–9.5.

Temperature affects the viscosity and stability of some polymers. Consider the following examples:

(1) Seven lb of Revert per 100 gallons of water at 45 °F yields Marsh funnel viscosity of 125 seconds per quart. The same mix at 85 °F yields 70 seconds per quart.

(2) A 0.87 weight mix of Revert at 68 °F yields a viscosity above 90 seconds per quart for three and a half days. The same mix at 80 °F maintains viscosity of 80 seconds per quart for only two days.

Polymer drilling fluids can break down viscosity. Without treatment, the viscosity of some polymers (Revert) completely breaks down in one to six days depending mainly on temperature; which is avoided by adding chlorine. Revert requires Fast Break; E-Z Mud needs sodium hypochlorite at a ratio of 2 quarts for every 100 gallons of water. Other polymers, such as E-Z Mud and Poly-Sal, maintain their viscosity for long periods of time since natural breakdown is not significant. Figure 4-11 lists additives for drilling fluids.

Polymer drilling fluids have virtually no gel strength because the colloids are nonionic and exhibit no attraction for each other. Most of the drill cuttings should be washed out of the borehole before circulation is stopped. A polymer fluid does not have thixotropic properties to hold cuttings in suspension. Shakers, desanders, or desilters are not needed when using polymer fluids. Since most of the cuttings are dropped out, friction and wear in the pump are minimized and the drilling rate is not impeded by cuttings or high density. A major advantage of polymers is the lack of mechanical wear to the drill-rig mud system.

Some drilled fines (clay, silt) circulate back down the hole. Recirculated solids are much less a problem with polymer fluids than with clay fluids. Revert will not hydrate in water containing any appreciable amount of borate. However, Borax can be used to produce a gel plug in hydrated guar-gum polymer. With a pH of 7.5, the borate cross-links the polymeric chains and forms a strong three-dimensional molecular gel. If a strong gel plug is necessary to get through a lost circulation zone, mix 1 cup of borax in 5 gallons of water and pour slowly into the pump section while pumping at idle speed. When the berated fluid (stringy gelled mass) recirculates, stop pumping for one-half hour. Resuming normal drilling should be possible after wasting the borated fluid. Repeat the procedure, if necessary. Although the polymer fluid is not thixotropic and has no gel strength, it thins somewhat while being pumped.

Polymer fluids build a type of membrane on the wall different from clay mud. Unnatural clay particles (bentonite) are not introduced into the hole. Since the polymer fluid is partly a thick solution, infiltration into the permeable wall is reduced. However, insoluble portions of some polymer colloids do exist. The insoluble and cuttings are surrounded with thick coatings that are more impermeable per unit thickness than a bentonite filter cake. The insoluble and cuttings seal the wall of the hole with a thinner, less active layer. The impermeable layer performs the same function as the filter cake in clay muds but does not restrict the annulus.
<table>
<thead>
<tr>
<th>Base Fluid</th>
<th>Additive/Concentration</th>
<th>Marsh Funnel Viscosity (seconds)</th>
<th>Annular Uphole 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></td>
<td></td>
<td>Increases viscosity (lifting capacity) of water significantly</td>
</tr>
<tr>
<td></td>
<td>15–25 lb/100 gal</td>
<td>35–55</td>
<td>80–120</td>
<td>For normal drilling conditions (sand, silt, and clay)</td>
</tr>
<tr>
<td></td>
<td>25–40 lb/100 gal</td>
<td>55–70</td>
<td>80–120</td>
<td>For gravel and other coarse-grained, poorly consolidated formations</td>
</tr>
<tr>
<td></td>
<td>35–45 lb/100 gal</td>
<td>65–75</td>
<td>80–120</td>
<td>For excessive fluid losses</td>
</tr>
<tr>
<td>Water</td>
<td>Polymer (natural)</td>
<td></td>
<td></td>
<td>Increases viscosity (lifting capacity) of water significantly</td>
</tr>
<tr>
<td></td>
<td>4.0 lb/100 gal</td>
<td>35–55</td>
<td>80–120</td>
<td>For normal drilling conditions (sand, silt, and clay)</td>
</tr>
<tr>
<td></td>
<td>6.1 lb/100 gal</td>
<td>65–75</td>
<td>80–120</td>
<td>For gravel and other coarse-grained, poorly consolidated formations</td>
</tr>
<tr>
<td></td>
<td>6.5 lb/100 gal</td>
<td>75–85</td>
<td>80–120</td>
<td>For excessive fluid losses</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></td>
<td></td>
<td></td>
<td>4,500–6,000</td>
<td>This range of annular uphole velocities is required for the dual-wall method of drilling</td>
</tr>
<tr>
<td>Air</td>
<td>Water (air mist) 0.25–2.00 gpm</td>
<td>N/A</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>N/A</td>
<td>50–1,000</td>
<td>Extends the lifting capacity of the compressor</td>
</tr>
<tr>
<td></td>
<td>1–2 qt/100 gal (0.25–0.5% surfactant)</td>
<td></td>
<td></td>
<td>For light drilling; small water inflow; sticky clay, wet sand, fine gravel, hard rock; few drilling problems</td>
</tr>
<tr>
<td></td>
<td>2–3 qt/100 gal (0.5–0.75% surfactant)</td>
<td></td>
<td></td>
<td>For average drilling conditions; larger diameter, deeper holes; large cuttings; increasing volumes of water inflow</td>
</tr>
<tr>
<td></td>
<td>3–4 qt/100 gal (0.75–1% surfactant)</td>
<td></td>
<td></td>
<td>For difficult drilling; deep, large-diameter holes; large, heavy cuttings; sticky and incompetent formations; large water inflows</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Injection rates of surfactant/water mixture:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Unconsolidated formations 3–10 gpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fractured rock 3–7 gpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Solid rock 3–5 gpm</td>
</tr>
<tr>
<td>Air</td>
<td>Surfactant/colloids/water (stiff foam)</td>
<td>N/A</td>
<td>50–100</td>
<td>Greatly extends lifting capacity of the compressor</td>
</tr>
<tr>
<td></td>
<td>3–4 qt/100 gal (0.75–1% surfactant) plus 3–6 lb polymer/100 gal or 30–50 lb bentonite/100 gal</td>
<td></td>
<td></td>
<td>For difficult drilling; deep, large-diameter holes; large, heavy cuttings; sticky and incompetent formations; large water inflows</td>
</tr>
<tr>
<td></td>
<td>4–8 qt/100 gal (1–2% surfactant) plus 3–6 lb polymer/100 gal or 30–50 lb bentonite/100 gal</td>
<td></td>
<td></td>
<td>For extremely difficult drilling; large, deep holes; lost circulation; incompetent formations; excessive water inflows</td>
</tr>
</tbody>
</table>

(Compiled partly from information presented in Imco Services, 1975; Magcobar, 1977; and Barold, 1980).

Figure 4-11. Additives for Drilling Fluids
The colloids in the polymer fluid are nonionic, have no chemical interaction, and are easier to remove in water-well development. When the viscosity of the fluid is broken, much of the cohesive function of the thin film becomes a water-like liquid and is washed out of the water well. Field testing of polymer fluids, using a falter press and a Marsh funnel, yields different results. The mud balance for measuring fluid density does not change. Weighing of the polymer fluid is limited, but by adding sodium chloride to the fluid the weight is increased up to about 10 lbs per gallon. The addition of heavy solids (ground barite) is ineffective because of the polymer fluid’s lack of thixotropic qualities.

b. **Mud Products.** Commercially processed clays for drilling are bentonite and attapulgite. Bentonite is superior except in brackish or salty water (use attapulgite in these waters). Bentonite forms naturally from decomposition of volcanic ash when ground. Bentonite consists of aggregates of flat platelets in face-to-face contact. Bentonite is mined in many states, but the best grade (Wyoming bentonite) is mined only in Wyoming and South Dakota. Wyoming bentonite contains sodium montmorillonite (the active part of the clay mineral) and is small in size, which is important in building viscosity.

Mud drilling fluids should be mixed with a mud gun. When agitated and sheared with water, the bentonite platelets absorb more than 25 times their own weight in water, separate, and swell. The amount of surface area wetted determines the ability of the particle to build viscosity. One ounce of Wyoming bentonite dispersed in water has more surface area than five football fields. Interparticle activity between platelets gives the mud its gel properties. The chemical composition of the mixing water affects the ability of bentonite to develop desirable qualities. These qualities are manipulated by adding small amounts of various chemicals.

c. **Mud Viscosity.** True viscosity is a term relating only to true (Newtonian) fluids, such as water, and is a proportional constant between shear stress and shear rate in laminar flow. Drilling muds act differently in that the proportion between shear stress and shear rate is reduced when shear rate is increased. Drilling muds are thixotropic. The viscosity of a drilling mud refers to the thickness of the mud while flowing. Gel strength is the term used to describe the thickness of drilling mud at rest. Gel strength develops over a short period of time.

Yield point is the mud quality broadly included in viscosity. More stress (pump pressure) is needed to cause the gelled drilling mud to start flowing than to sustain flow once the gel is broken. The stress required initiating shear or flow is the gel strength of the mud. The stress required to maintain shear is the viscosity. A higher yield strength is required with respect to the gel strength so the mud becomes very thin in flow shear.

The primary function of viscosity is to help lift drill cuttings from the borehole. Other mud characteristics affecting lifting capacity are density, velocity, and flow patterns. Gel strength holds the cuttings in suspension at the bottom of the hole when circulation is stopped. The stress (hydraulic pressure) required to break the gel strength to initiate cumulation can be detrimental. Required bottom-hole pressures can cause fracturing or opening of fractures in the formation, resulting in loss of drilling fluid, formation damage, and borehole wall damage. Down-hole pressure required to continue circulation depends on friction, density (or weight of fluid column), and viscosity of the mobilized fluid. These pressures can also cause serious problems. Therefore, it is desirable to use a drilling mud of relatively low density and viscosity, moderate gel strength, and high yield point relative to the gel strength (a very thin fluid in circulation).

d. **Mud Testing.** A Marsh funnel (see Figure 4-12) is routinely used to give an indication of thickness or apparent viscosity of drilling fluid. A Marsh funnel is 12 inches long and 6 inches in diameter and has a No. 12 mesh strainer and a 1,000-milliliter (ml) cone. The funnel has a 2-inch-long, calibrated, hard-rubber orifice with an ID of 3/16 inch. The funnel’s cup is marked with a capacity of 1,000 ml. Use the following procedure when using a Baroid Marsh funnel:

1. Hold or mount the funnel in an upright position, and place a finger over the hole.
(2) Pour the test sample, freshly taken from the mud system, through the screen in the top of the funnel until the level touches the top of the screen.

(3) Immediately remove the finger from the outlet tube, and measure the number of seconds for a quart of mud to flow into the measuring cup.

(4) Record time in seconds as funnel viscosity.

Note

Calibration time for fresh water at 70 °F is 26 seconds.

(5) The funnel viscosity measurement obtained is influenced considerably by the gelation rate of the mud sample and its density. Because of these variations, the viscosity values obtained with a Marsh funnel cannot be correlated directly with other types of viscometers and/or rheometers. Graduated in cubic centimeters (cc) and fluid ounces, the 1,000-cc measuring cup is designed specifically for use with a Marsh funnel viscometer. A quart volume is clearly marked on the measuring cup.

The desired mud consistency depends on many factors. The nature of the formations will dictate mud qualities. However, all conditions will not be known before drilling is started. The inexperienced driller must be careful because mud with the correct thickness often is too thin; although viscosity is adjusted by adding water or clay. A good range for drilling muds is 32 to 50 seconds per quart. Viscosity is influenced by mud density, hole size, pumping rate, drilling rate, pressure requirements, and geology. Considering the thixotropic qualities of drilling mud, a funnel viscosity of 100 seconds per quart may be no more viscous than a funnel viscosity of 50 seconds per quart if both fluids are in motion.

Test readings are a useful indicator of changes in mud that might lead to problems. Therefore, conduct Marsh-funnel tests before beginning OPS and record the findings. Take mud samples for each test from the same location in the circulating system just before returning to the hole. The apparent viscosity of the drilling mud in motion affects carrying capacity, the pump pressure (hydrostatic down-hole pressure) required for circulation, and the ability to drop cuttings in the settling pit. These characteristics are also intrinsically involved with well hydraulics, density of mud, density and size of cuttings, and particle slip.

e. Density. The carrying capacity of a mud is affected by its density and the density of the drill cuttings. If the cuttings are denser than the fluid, they descend. The magnitude of the difference in density, particle size, and fluid viscosity affect the rate at which a particle descends. Particle slip denotes this downward movement through the fluid. Ignoring thixotropy, the actual downward particle slip is constant regardless of velocity of flow. However, when the upward velocity of fluid exceeds the downward
particle slip, the new movement of the particle is upward. Up-hole velocity plays a major role in determining the carrying capacity of the cumulating fluid. The practical limits of up-hole velocity depend on pump size and capacity, ID of the drill string, jet size in the bit, viscosity of the fluid, cross-sectional area of the annulus, and stability of the borehole wall. Up-hole velocity is not as simple as the comparison of pump capacity, drill string ID, and annulus. Up-hole velocity is not a constant.

The density of the drill fluid serves other purposes in rotary drilling. Heavy fluids can control (hold down) formation pressures encountered in drilling. Heavy mud is built by adding a weighing material such as ground barite (specific gravity 4.25). Prepare drilling mud in excess of 20 lbs per gallon by using barite. First, mix bentonite and water to build viscosity. Then, add finely ground barite so the mud will hold the barite in suspension. Use heavy drilling mud only when absolutely necessary to control pressures since the muds have disadvantages. High-density mud increases pressure on the formation by the weight of the fluid column. Figure 4-13 shows the nomograph for determining the hydrostatic head produced by drilling fluids. The increased pressure is further increased by the pump pressure required to mobilize the fluid in circulation. The increased pressure can cause formation damage and loss of circulation. In formations that are strong enough to withstand the pressures without being damaged, the drilling operation can still suffer.

![Figure 4-13. Nomograph for Determining Hydrostatic Head Produced by Drilling Fluids](image)
The pressures from the mud and the formation should be balanced so that the borehole bottom exposed to the drill bit is near surface eruption from pore pressure. That balance makes the formation easy to fracture and enhances the cutting rate. If the mud pressure is much lower than the formation pressure, instability occurs in the borehole. If the mud pressure far exceeds the formation pressure, the cuttings may be suppressed and reground by the bit. The result of recutting reduces bit life and lowers drilling rate. Mud density is increased by drill cuttings; the mud rising in the hole is heavier than the mud returning to the hole.

All cuttings should be removed from the drilling mud in the settling pits and not recirculated. Although 100 percent removal is unrealistic, well-designed mud pits and mechanical screens, desanders, and desilters materially aid in removing cuttings from the mud. Water weighs 8.34 lbs per gallon. Clean, low-solid bentonite mud can weigh 8.5 to 9.0 lbs per gallon; try to maintain that weight. Increasing density of the mud during drilling indicates that the mud contains native solids. The drill’s penetration rate could be exceeding the combined effort of the mud pit, desanders, and fluids to effectively separate solids from the drilling mud. To correct this problem, slow down the penetration rate and run the desanders to remove the solids.

The density or weight of the drilling mud is determined by using a mud balance. Fill the mud-balance cup with mud, and place the inset lid in the cup. Excess mud is displaced through a hole in the lid. Clean the outside cup area, place the assembly on the center pivot, and balance it using sliding weight. Read mud density as lbs per gallon and lbs per cubic ft. If the mud weight that enters and exits the drill hole is known, an evaluation of the efficiency of the mud pit and mechanical separators is achievable. It is also possible to determine when to clean the mud pit and tell how well the mud is cleaning the hole. If samples are only taken from one location, it should be from the return end of the pit.

f. Filter Cake. Filter cake consists of solids from the drilling mud deposited on the borehole wall as the water phase is lost into the formation. Desirable properties are thinness and impermeability. Drilling mud is a colloidal suspension that is separable by simple filtering. With the hole kept full of mud, the hydrostatic pressure inside usually exceeds the formation pressure. Occasionally, an artisan aquifer is penetrated, with formation pressure higher than the hydrostatic in-hole pressure. When the borehole pressure is higher than the formation pressure, the drilling mud tends to penetrate more permeable formations. Solids from the mud filter out and deposits on the wall while the liquid phase of the mud (filtrate) enters the formation.

Filter cake is compacted against the wall by the excess hydrostatic pressure in the borehole. If the drilling mud is a well-conditioned bentonite and water mixture, most of the solids plastered against the wall become flat platelets of highly active clay. The filter cake is self-regulating based on its degree of impermeability. As long as filtrate passes through, the filter cake continues to thicken. A thick cake detrimentally increases down-hole cumulating pressure by restricting the annulus, making it difficult to pull the drill string because of the physical size of the drill collars and bit. In deep and somewhat deviated holes, the danger of key seating increases. Because a thick filter cake is of a lower quality and depends on its thickness to be effective, it is more easily damaged and eroded. A thick filter cake may indicate that the fluid has a high percentage of native solids; requiring a cleaning of these solids from the mud before drilling progresses.

A thin, highly impermeable filter cake bonds well to the wall and provides a surface for the hydrostatic pressures to act against to support the wall. Filtrate loss into the formation accounts for significant fluid loss, if the consistency of the drilling mud is not good. Good consistency does not necessarily mean thick; it has to do with the bentonite content and the quality of filter cake. If a permeable formation is encountered with pore spaces too large to be plugged by the fine bentonite particles, the drilling mud enters the formation. That mud loss takes the entire output of the mud pump. The drill cuttings being carried up the annulus is sometimes beneficial. The cuttings are coarser than the bentonite particles and may help bridge across formation pores. If this technique is used, maintain the normal drilling rate to supply the cuttings. Slow down the pumping rate to reduce pressure on the formation while bridging the open spaces. With sufficient bridging, a suitable filter cake follows, circulation is regained, and normal drilling OPS are resumed.
In the field, the filtration properties and filter-cake thickness is tested using the filter-press kit. This kit consists of a press with a mounted pressure gauge and a CO2 charging system that is used to simulate the hydrostatic pressure inside a 200-foot hole. By placing a sample of drilling mud in the press and charging the system, a filter cake is formed. The filter cake should be less than 2/32-inch thick.

g. **Salty Environment.** A high chloride content in the mixing water causes bentonite to react anomalously or not react at all. The ground bentonite remains agitated; it does not disperse, hydrate, or swell. In salt water, bentonite is an inefficient clay additive for drilling mud. The dissolved salt is an electrolyte that changes the interparticle activity of bentonite. If a sufficient amount of salt water is added to a fresh water and bentonite mud mixture, the dispersed platelets forms lumps. Viscosity and filtrate loss increase and the mud’s ability to build a thin, impermeable filter cake decreases.

Attapulgite is often used for salty formations. The small particles produce a high surface-area-to-volume relationship and good viscosity building. Unlike bentonite, the particle shape is needle-like. Viscosity building in attapulgite depends on the entanglement of these needles. The disorderly arrangement of the particles accounts for the poor filtration qualities of attapulgite. The filter cake is more like a layer of strew or sticks. Attapulgite clay does not have the physical qualities to build a thin, impermeable filter cake. If bentonite is first mixed in fresh water with salt water added as make-up water, the bentonite flocculates; that flocculation is reversed by chemical treatment.

h. **Well Hydraulics.** A basic understanding of well hydraulics is paramount. Fluid is pumped down the drill string, out the ports in the bit, and up the annular space between the drill string and the wall. The fluid empties into the mud pit, through any mechanical solids separating equipment, and is picked up from the pit by the mud pump for recirculation. The system is intended as a conservation system. Except for mud lost into the formation or where artisan water exceeding hydrostatic pressure flows into the hole, the return is largely complete and the mud-pit level does not change. Even if these systems are in equilibrium, an understanding of the up-hole rearrangement of flow patterns is necessary.

Fluids flow in two distinct patterns; laminar and turbulent. Laminar flow is orderly. The streamlines remain distinct and the flow direction at every point remains unchanged with time. Turbulent flow is disorderly. The flow lines and directions are confined and heterogeneously mixed. The type of flow depends on the cross-sectional area of the fluid course and the velocity, density, and viscosity of the fluid. In water-well drilling, the cross-sectional area of the annulus is usually several times that of the ID of the drill string. Because of the increase in volume in the annular space, flow at the point the fluid leaves the bit is turbulent. The fluid becomes laminar flow when it begins flowing up the annular space. The returning fluid velocity is slower and the drill fluid is denser and probably has more apparent viscosity, which affects the flow pattern. To clean the hole and carry the drill cuttings out, turbulent flow in the annulus is better.

Picture the flow in the annulus as a series of nested tubes. Velocity varies as if these tubes were sliding past one another while moving in the same direction. Flow near the wall and near the drill string is at a slower rate than near the center. Cuttings near the center are vigorously lifted while cuttings near the wall and drill string actually slip in a net fall. Rotation of the drill string changes the flow pattern near the drill string and materially enhances particle lift.

For example, when using a 3 1/2 -inch ID and 4-inch outside diameter (OD) pipe to drill a 9-inch hole and pump 200 gpm, the velocity of the ID pipe is 400 fpm and the velocity of the OD pipe is 75 fpm. To test cumulation at these rates (bit is 300 ft deep), pump down a marker (strew or oats). The majority of the material should take four minutes and 45 seconds to return (300 ft at 400 fpm takes 45 seconds and 300 ft at 75 fpm takes four minutes). To clean all the cuttings from a 300-foot depth with an average up-hole mud velocity of 75 fpm requires more than four minutes of pumping. Consider this concept regarding sampling cuttings from the return mud.

If cuttings remain in the annular space between the drill rod and borehole wall when circulation is stopped, they produce a denser fluid than the clean drilling mud inside the drill rods. The denser mud in the annular
space then flows down the hole and forces the clean drilling mud up the drill rods. This causes a geyser effect, and the drilling mud may shoot several ft into the air until the mud columns equalize (some drillers mistake this for a caving hole). If this situation happens when adding drill rods, increase the circulation time after drilling down the next rod. Use the following formula to calculate the annular space volume:

$$V = \frac{(D^2 - d^2)(5.5)(L)}{1,000}$$

where:

$V$ = annular space volume, in cubic ft.

$D$ = hole diameter or bit size, in inches (refer to Figure 4-8)

$d$ = drill hole or drill steel collar diameter, in inches (refer to Figure 4-8)

$L$ = hole length, in ft (refer to Figure 4-8)

i. **Mud Pits.** Rotary chilling preparation is the design and excavation of an in-ground mud pit or installation of a portable mud pit and the mixing of the drilling fluid. For standard drilling OPS that use well-completion kits, well depths could range from 600 to 1,500 ft. For wells up to 600 ft using the 600-foot well drilling system (WDS), use portable mud pits. For wells over 600 ft, use dug mud pits. In either case, clean the cuttings from the pits as drilling progresses. Design considerations include the anticipated depth and diameter of the drill hole, since the material cuttings from the hole is deposited in the mud pits.

The volume of the pits must equal the volume of the completed hole. Therefore, during drilling, clean the cuttings from the pits frequently. The size and depth of the pits are not critical if a backhoe is on site to dig and clean the pits. If pits are dug and cleaned with shovels, width and depth are important. Drilled cuttings should drop out of suspension in the mud pit. Therefore, long, narrow pits are better. Figure 4-14 shows a mud-pit layout and a chart depicting mud pit capacities and dimensions.

**Note**

Portable mud pits require constant cleaning.

Mud pits are part of the circulating system for mixing and storing drilling fluid and for settling cuttings. The ground slope affects site layout. Pit design enhances pit performance. Most drillers agree using multiple pits is best when dropping drill cuttings from the fluid. The volume of the pit should be one and one-half to three times the volume of the hole. This provides fluid to fill the hole and an excess volume to allow stilling and settlement or processing before returning to the drill string. A volume of three times the hole volume minimizes drilling-fluid and mud-pit maintenance. Figure 4-15 shows a mud pit that is prepared on-site. Figure 4-16 shows a portable mud pit.

If drilling mud is processed through shale shakers, desanders, desilters, and space and time for cuttings settlement are not important. Long, narrow pits connected at opposite ends by narrow, shallow trenches are preferred. If using a polymer fluid that has no thixotropic qualities, the settlement of cuttings is a function of time at low velocity or no flow. With polymer fluid, a long-path mud pit is ideal; if part of the flow almost stops, cutting settlement is enhanced.

If a clay-based mud with thixotropic qualities is used and the mud moves slowly or flow stops, the gel strength can hold the cuttings. High velocity through narrow, shallow trenches holds the cuttings in suspension. If mud runs over one or more wide baffles or weirs, flow shear and velocity are low. These factors enhance cuttings to drop out. If mud processing equipment is available, use it. Recirculating clean fluid reduces power requirements, wear, and erosion and enhances drilling rate.
1. Rectangular Mud Pit
   Volume (gal) = Length (ft) x Width (ft) x Depth (ft) x 7.5

2. Pit with Slope Sides
   Volume (gal) = Length (ft) x Average Width (ft) x Depth (ft) x 7.5
   \[ \text{Average Width} = \frac{\text{Width at Top} + \text{Width at Bottom}}{2} \]

3. Ideal Dimensions for Two Basic Pits
   In general, the pit should be three times the volume of the finished borehole. Each mud pit should have a settling section and a suction section. The dimensions of the settling pit are determined by using a basic equation to establish the width. Once the width is known, calculation of the length and depth is possible.
   \[ \text{Width} = \sqrt[3]{\frac{\text{hole volume (gal)} \times 2}{2.125 \times 7.5}} \]
   where:
   \[ \text{Length} = 2.5 \times \text{Width} \]
   \[ \text{Depth} = 0.85 \times \text{Width} \]
   *For the suction pit, the length is 1.25 x Width and the Depth is 0.85 x Width*

Figure 4-14. Mud Pit Layout with Pit Capacities and Dimensions
Figure 4-15. Mud Pit Prepared on Site

Figure 4-16. Portable Mud Pit
6. **Rotary Drilling Problems.** Some problems in rotary drilling are minor and others are serious and result in failure to complete a hole or even loss of equipment. Many serious problems start minor, but become serious if not recognized or handled properly. For example, in a loose sand zone, the borehole walls can slough and cause drilling fluid loss. By reducing or increasing fluid velocity, stabilization of the wall and regaining fluid circulation is possible. However, if the condition is not recognized and drilling continues, the wall will slough and create a cavity. The cuttings lose velocity, become suspended in the cavity, and tend to fall back into the hole when rods are added; which may result in the rods or the bit becoming stuck in the hole. Other problems may result from subtle changes in geology, imbalances in the drilling operation, or equipment failure.

   a. **Lost Circulation.** Lost circulation refers to a loss in volume of drilling fluid returning to the surface. The implication is that some fluid pumped down the drill pipe is entering the formations. The mud pit may lower, since some of the mud is used in forming a mud cake on the borehole wall; however, increased lowering can indicate circulation loss. Losses may occur through open-graded sand or gravel or open joints in rock. A loss may occur when cuttings are not washed out and the borehole annulus becomes restricted, resulting in increased down-hole pressure. Spudding (raising and lowering the drill string) the hole too violently may cause loss. Spudding helps wash cuttings, but down-hole pressures increase momentarily. Experienced drillers are able to estimate when spudding is safe. The driller is blind when fluid cumulation is lost and drilling continues. An experienced driller that knows the rig can often drill blind successfully, but reestablishing circulation is always safer.

   Reestablishing circulation involves one of several techniques. Commercial items such as chopped paper, straw, cottonseed, and nut hulls may be added to the mud pit. Sometimes, while the loss zone is grouted and redrilled, the grout is lost into the formation. Commercial drilling additives such as a polymer may be used to reduce fluid loss in some formations. In this situation, the casing may be set through the loss zone. Occasionally, drill cuttings plug the loss zone by reducing fluid velocity while continuing to drill. Reestablishing circulation is usually a trial-and-error process. The longer a drill is without circulation the more difficult it is to reestablish circulation.

   b. **Fall-In.** Fall-in is material that accumulates in the bottom of the borehole after cumulation is stopped. This material is borehole-wall material that results from sloughing or caving or cuttings previously carried in suspension. Fall-in occurs when a loose, unstable formation is encountered and the drilling-fluid weight is insufficient to stabilize the formation. If a fall-in is suspected or anticipated, raise the drill bit off the bottom of the hole (20-foot minimum) each time drilling is interrupted. This prevents the cuttings and fall-in from settling back around the bit until the problem is solved.

   c. **Stuck Drill String.** The drill bit and any collars just above the bit are larger in diameter than the drill pipe. The string becomes stuck when cuttings collect on the bit and collar shoulder. This condition is called sanded in. Be careful because the drill pipe may break while trying to remove the drill string. Regaining circulation and working the sand out are seldom successful. If the formation does not take the fluid when the pump clutch is engaged, the relief (pop-off) valve operates to relieve the pressure. Not many actions will free the drill string except to wash a small pipe down the annulus to the bit and jet the settled sand back into suspension. When the annulus is too small to pass a jet pipe, a part of the drill string may be lost.

   **WARNING**

   Never try to stop the relief-valve operation to get higher pressure. Do not override the relief valve; it protects equipment and operators.

   When the annulus is small, excessive up-hole velocity promotes erosion of the filter cake in granular zones and allows caving against the drill pipe. If this occurs, try to maintain circulation and rotation,
even if circulation is slight. Where the grains are angular, the drill pipe may become locked while being rotated. This situation is similar to a sanded-in bit. With smooth pipe (not upset), hammering up and down may sometimes dislodge the string; allowing the reestablishment of circulation and the continuing of drilling. Be careful because hammering up and down may produce unfavorable compacting of the sand. In a hole of fine-grained soil or shale, where the alignment has significantly deviated and the drill pipe has wallowed into the wall, the pipe may become wall stuck. Pipe friction and relatively high borehole pressure may move the pipe tighter into the wallowed groove as the string is pulled. An alert driller should recognize early stages of deviation and take measures to realign the hole.

d. **String Failure.** When the drill string parts, leaving a portion in the borehole (a fish), the drill string is rung off. Attempting to retrieve the lost portion is known as fishing. Fishing tools include a tapered tap and an overshot die (see Figure 4-17). Ringing off is normally fatigue failure in the drill-rod joints caused by excessive torque or thrust (repeated flexing and vibration that crystallizes heat-treated tool joints) or by borehole deviation (with flexing of the string). Examine drill rods for signs of failure, frequently.

e. **Deviation.** A deviated borehole is called going crooked. If the initial setup is made without plumbing the kelly, the borehole will likely go crooked. A crooked borehole usually amplifies other problems and makes a borehole unsuitable for a well. However, always anticipate deviation since the borehole naturally tends to spiral from bit rotation. Variations in the formation badness may start deviation. Excessive bit loads magnify minor initial deviation. Use all available guides and collars and a reduction in bit load to minimize deviation.

f. **Swelling Soil.** The in-hole effects of swelling soil (shale or clay) that absorbs water from the drilling fluid is squeezing. The result is a borehole that is undergauged to the extent that pulling the bit by normal hoisting methods is not possible. In such cases, cutting through the blockage with a roller rock-bit or a drag bit may resolve the issue. Swelling causes caving and failure of the wall. Keep water out of the formation to prevent swelling. Special polymer drilling fluid additives that limit water absorption are available. High quality bentonite forms a thin, but highly impermeable filter cake.

Figure 4-17. Fishing Tools
4.2 AIR ROTARY DRILLING

Air rotary drilling is similar to mud rotary drilling except that the fluid circulated is compressed air. The air is not recirculated. Using compressed air is advantageous when water for drilling is inconvenient, fluid is being lost to the formation while drilling, or it is difficult to wash sticky clay formations from the hole. Also, air rotary drilling requires much less development time. However, air rotary techniques may need adjustment with each well drilled. Some disadvantages to air rotary drilling are that air cannot support the wall of a hole in an unstable formation, changes in the return air flow are not as readily apparent as in mud flow, and air is not as effective in cooling and lubricating the drill bit and string. The list below describes air rotary drilling in more detail:

1. **Air Supply.** Air has no density or viscosity, so cuttings are blown out of the hole at high velocity. The up-hole air flow is turbulent and more effective in lifting the cuttings. The lack of density and viscosity increases the particle slip so a continuous and high velocity up-hole flow must be maintained to keep the hole clean. An upward velocity of about 4,000 fpm is sufficient to clean cuttings out of the hole. Cutting removal also depends somewhat on size, density, and amount of cuttings. Up-hole air velocity is computed by dividing the output volume of the air compressor, in cubic feet per minute (cfm), by the cross-sectional area of the annulus of the hole, in ft. Air compressors are rated on the following items:

   a. Intake air volume.

   b. Condition. Compressors wear with use, causing capacity to decrease.

   c. Sea level. Output volume capacity is reduced about 3.5 percent for every 1,000 ft above sea level.

   d. Temperature. Efficiency is reduced when temperatures are above 60 °F and is increased when temperatures are below 60 °F.

   e. Rotation speed. Output from the compressor is directly proportional to the motor’s rpm. Do not operate a compressor at lower rpm to reduce wear.

Dry material drilled by air creates a large amount of dust when blown from the borehole. Inject water to control the dust. Depending on the nature of the material drilled, the amount of water could be 1/2 to 5 gpm. Water injection increases air density and improves carrying efficiency for the cuttings. Adversely, water causes the cuttings to stick together, making them heavier and harder to blow out of the borehole, or the cuttings may stick to the borehole wall, causing constriction.

Minor wetting or dampening makes some walls more stable; excessive wetting causes a wall to fail. Adjusting the amount of water injected into the borehole takes experience. Air has no wall-stabilizing qualities. In soils where sloughing and caving are a problem, injection of a thin drilling mud (bentonite mixed with the injection water) controls the dust and contributes to stability.

In drilling large diameters (12-inches) with standard drill pipe (3 1/2 inches OD), the annulus equals 0.7 square ft. Using a 1,000-cfm compressor the up-hole velocity would be about 1,400 fpm, which is not enough velocity to remove cuttings. While penetration progresses, the cuttings tend to stay at the bottom of the borehole under the drill bit and are recrushe. These cuttings act as a pad under the teeth of the bit and prevent proper cutting action. The compressor normally cannot drill holes by straight air rotary.

Use the following equations to estimate compressor size, up-hole velocity, and hole-size requirements for air drilling or Figure 4-18 to determine up-hole velocity. The recommended up-hole velocities are: 3,000 fpm, minimum; 4,000 fpm, fair; and 5,000 fpm, good.

\[ V_{\text{min}} = (D^2 - d^2)^{16.5} \]

where:
\( V_{\text{min}} = \text{minimum velocity, in cfm.} \)

\( D = \text{hole diameter or bit size, in inches (refer to Figure 4-8).} \)

\( d = \text{drill steel or drill collar in diameter in inches (refer to Figure 4-8).} \)

and

\[
V = \frac{C}{V_{\text{min}}}
\]

velocities are: 3,000 fpm, minimum; 4,000 fpm, fair; and 5,000 fpm, good.

where:

\( V = \text{actual up-hole velocity, in fpm.} \)

\( C = \text{compressor capacity, in cfm.} \)

\( V_{\text{min}} = \text{minimum velocity, in cfm.} \)

---

**Figure 4-18. Nomogram to Calculate Up-hole Velocity**
Air drilling has a depth limitation because of water in the borehole. Air pressure must displace the head of water in the borehole before it can exit the bit. An advantage is that when water is encountered, it discharges with the air. As drilling progresses, an estimation of the amount of inflow to the well is possible. When calculating the static head of water, remember that 0.434 psi equals 1 foot of head or 1 psi equals 2.3 ft of water. For example, the minimum psi required to overcome a 400-foot static water-level column is 173.6 psi (400 ft x 4.34 psi = 173.6 psi).

2. **Foamers.** Commercial foamers for drilling enhance the air’s ability to carry cuttings and reduce the velocity required to clean the borehole. The foamer is mixed with the injection water, but does not foam with gentle stirring; therefore, pumping is not hindered. Foam must be pumped at a pressure greater than the air-line pressure into which it will be injected. The foaming and mixing with air largely occurs when exiting the drill bit. If air flow is reduced from the volume required for air rotary drilling and the injection rate is tuned to the airflow, the foam leaves the hole as a slow-moving mass (see Figure 4-19). The foam is laden with drill cuttings and the borehole is effectively cleaned with only 10 percent of the air volume required had foam not been used. Boreholes of 2 ft or more in diameter are possible with a well-tuned air-foam operation using air compressors. Figure 4-20 illustrates a list of common problems with air-foam systems.

Commercial foamers vary and come with mixing instructions on the container. Only a few foamers are necessary to produce large volumes of rich foam. Less than one quart of foamer mixed with 100 gallons of water injected at a 2- to 3-gpm rate is sufficient for a 12-inch diameter borehole. The column of foam provides slight stabilization to the wall. Increasing the richness and density of the foam is possible by mixing bentonite with the injection water before adding the foamer. A very thin fluid of 15 to 20 lbs of bentonite mixed in 100 gallons of water is suitable for injection in air-foam drilling.

Adding foamer to this fluid in the same proportions as clear water, results in richer, more stable foam. This technique is sometimes called air-foam-gel drilling. The gel refers to the bentonite fraction. Because of the increased richness, stability, and density of the air-foam gel, the air’s cutting-carrying capacity and the wall stabilization are enhanced. Foam reaching the surface must be carried away from the drill rig to avoid mounding over the work area. Foam eventually dissipates when exposed to the atmosphere. Use either of the following methods to remove the foam from the rig area:

![Figure 4-19. Foam from the Well](image-url)
### Problem | Reason for Occurrence | Corrective Adjustment
--- | --- | ---
Air blowing free at the blooey line with a fine mist of foam | Air has broken through foam mix preventing stable foam formation | Increase liquid injection rate or decrease air injection rate
Foam thin and watery | Formation water entry with possible salts contamination | Increase liquid and air injection rates, and possibly increase percent of foaming agent
Quick pressure drop | Air has broken through foam mix preventing formation of stable foam | Increase liquid injection rate or decrease air injection rate
Slow, gradual pressure increase | Increase in amount of cuttings or formation fluid being lifted to surface | Increase air injection rate slightly
Quick pressure increase | Bit plugged or formation packed off around drill pipe | Stop drilling and attempt to regain circulation by moving pipe

Figure 4-20. Common Problems with Air-Foam Systems

- Method 1. Use a packer to seal the top of the surface casing around the drill pipe or kelly bar so either rotates freely. Fit the top of the surface casing with a T pipe below the packer for connecting a waste pipe. As foam comes out of the waste pipe, remove it from the rig.

- Method 2. Place a T pipe at the top of the casing with an air-line eductor that causes a vacuum at the top of the hole. The foam is vacuumed into and blown through the waste pipe. By using an eductor, returning foam is observed and regulated. The eductor is fabricated and the drilling operation does not usually require the full output of the compressor.

### 4.3 PERCUSSION DRILLING

This type of drilling involves crushing by impact of the teeth of the drill bit. Most percussion drills are actuated by compressed air (pneumatic percussion). Essentially, percussion drilling for water wells uses down-hole, pneumatic-percussion hammer drills. Down-hole means the percussion motor (actuating device) is at the bottom of the drill string.

Percussion drills are best suited for drilling brittle, moderately soft to hard rock. In hard rock with percussion drills, drilling is faster and more economical than with other drilling methods. The air blows the cuttings from under the bit and up the annulus to the surface. The air’s ability to carry the rock chips depends primarily on high air velocity. An up-hole velocity of about 4,000 fpm is required to remove cuttings. If drill penetration rates are high (30 fpm or more), a higher up-hole velocity is needed to clean the hole. To drill water wells with percussion drills, balancing drill perimeters with the materials is paramount.

Down-hole hammer drilling with a large diameter hammer or bit (see Figure 4-21) usually results in a very crooked hole unless drill stabilizers are used or the hole is drilled in two steps. For two-stage drilling, drill a small pilot borehole with a 6- to 6 1/2-inch bit on a small hammer using drill collars as stabilizers. Enlarge the borehole using a stinger bit for drilling. The list below describes percussion drilling in more detail:

1. **Equipment.** Shallow holes for loading explosives in rock quarries and other excavations are usually drilled by percussion. Percussion drills are used because they penetrate quickly, even through hard rock. Most percussive motors or actuating devices are above ground. Top-head percussion drilling is not practical for deep boreholes because too much energy is lost in the long drill string. The down-hole drill was developed for efficiency. This drill is adaptable to most rigs and can drill water wells to depths exceeding 2,000 ft. To operate the drill, hoist, handle, and rotate the drill string as well as the drill motor and have an adequate air supply. Supplementing the air supply with an auxiliary (tag-along) compressor is possible when necessary through simple plumbing.

During operation, an air-actuated piston impacts the drill-bit shank. Porting within the drill case forces the piston up and down with the full force of the air pressure. The drill-bit shank is splined and is slide in the splines about 2 inches until fully extended. The bit is held in the drill by a retainer ring and may have several design shapes. Currently, all down-hole bits are set with carbide buttons specifically formulated
for the percussion application. The carbide button bit is more durable than other bits made from hardened steel. However, the drill bit dulls and buttons flatten from wear. A dull bit is less efficient, works harder, is easily damaged, and has a reduced production rate.

A green stone is able to reshape a flattened carbide button. An experienced operator recognizes excessive wear and knows when to reshape the button. A percussion drill bit should drill 1,000 ft or more in hard rock without reshaping. A properly maintained bit has the longest service life and drills the most economical holes. Sharpening and reshaping the carbide buttons are detailed procedures. See the manufacturer’s service manual for these procedures. The object of reshaping the button is to restore the hemispherical shape without removing excessive carbide material. The cutting points on a reshaped bit are be about equal in length. The flat area of each button is symmetrical around the cutting point and each button wears equally, which makes reshaping simple. Marking the center of the flat with ink represents the original cutting point and is the same length from the bit body as the other buttons. Carefully grind the worn button to a round shape leaving a flat (1/16-inch diameter) at the ink mark. Grind each button consistently; realizing that the reshaped buttons will not be perfect.

2. **Power**. Operating the down-hole drill is not difficult. Percussion drills are designed to operate at air pressures of 150 to 350 psi. The percussion drill is an orifice that leaks air out of the system. Air passing through the percussion drill actuates the piston and exhausts into the hole. The air volume used to actuate the drill is consumed by the drill. As the air consumption of the percussion drill increases, the air pressure delivered to the drill increases (see Figure 4-22). For example, if a percussion drill consumes 150 cfm of air at 200 psi, a compressor that maintains 200 psi while losing 150 cfm of air to the drill at 200 psi is needed.

Compressors are positive displacement air pumps. Pressure is a function of chamber ratio and leakage within the displacement mechanism. For example, a 200-psi compressor produces 200 psi in a closed receiver while turning a few rpm. The volume of air produced is a function of the displacement chamber, size of the cylinders or rotors, and the speed of rotation. Volume output is directly proportional to speed of rotation. Efficiency of the compressor is adversely affected by wear within the compressor and the elevation and ambient temperature.

Energy output from any drill is directly proportional to the air pressure delivered to the drill (see Figure 4-22). The percussion drill reacts to a pressure differential between intake and exhaust. The pressure delivered to the drill is somewhat less than the gauge pressure at the compressor because of friction loss in the plumbing; pressure in the borehole increases with depth because of friction and the load of cuttings and water. Increased pressure in the borehole reduces the effective pressure differential across the drill. The friction losses in plumbing and pressure at the bottom of the hole are calculable, but the calculations are not very useful. When drilling, the hammer is heard operating in the hole when it reaches the bottom. If the hammer fails to start operating, do not let the bit rotate on the bottom of the hole because it could destroy the buttons.
### Table 4-22. Air Consumption

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<th>Choke Size (inches)</th>
<th>Free Air Consumption of Tool (scfm)</th>
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</table>

3. **Procedure.** Attach the percussion drill to the drill string or drill kelly and lower the drill until the drill sets on the material. Extend the drill bit (open position) in the splines. If air is applied with the drill bit extended, the air blows directly through the drill and the drill does not function (the piston is not actuated). Weight applied on the drill must be sufficient to push the drill bit into the drill (closed position) while holding it closed. While maintaining the load, apply air pressure and slowly rotate the drill. When these actions are balanced, the drilling operation is optimal. Balance is attained by experimenting during drilling.

   a. **Weight on Bit.** The weight applied to the drill must be sufficient to hold it in the closed position while drilling. While the drill bit is splined and moves in relation to the drill, the bit should not move in the splines while drilling. The required weight on the bit (bit load) varies somewhat with percussion drills from different manufacture. With a given drill, the bit load varies with the air pressure used for drilling. The air pressure does not tend to enter the drill bit (open position), however, the energy with which the piston strikes the bit shank is directly proportional to the air pressure applied. Consequently, more bit load is necessary to keep the bit in the closed position with higher air pressure. See the manufacturer’s manual for specific recommendations for minimum bit load. The range for a 6-inch drill generates about 2,500 lbs total bit load at 125 psi to 4,000 lbs total bit load at 200 psi. Increasing bit load above the recommended minimum does little to increase the drilling rate. To achieve an increase in production rate, add weight if it does not adversely affect the rotation speed or constancy. Too much bit load will:

   (1) Affect the constancy of the rotation, which is detrimental to drilling production rate.

   (2) Damage the drill.

   (3) Cause excessive wear and premature failure of the bit.

   b. **Plumbness.** Water wells should be plumb and straight. Apply bit load by using drill collars to hold the drill string in tension. Most rigs have a mechanism designed for that purpose. Because the drill string is relatively flexible, loads applied from the top cause the drill string to flex and may misalign the drill bit. This procedure causes the drill to deviate from vertical and continued top loading exaggerates deviation. Apply bit load by adding heavy drill pipe sections (drill collars) at the bottom of the drill string just above the bit. If a sufficient load is added at the bottom, the drill string is held in tension while drilling. The borehole tends to be straight because of the pendulum effect. Borehole deviations from vertical are sometimes associated with fast drilling rates. Such deviations actually result from crowding the bit (trying to increase the penetration rate by overloading the bit).

   c. **Air Pressure.** Exceeding the 350-psi rating of the drill is not possible with the supplied compressors. The energy output of the drill is proportional to the air pressure delivered. Try to operate the drill at the maximum air pressure available. Lubricate the drill, using an in-line oiler designed for operation at the maximum anticipated working pressure. To control dust, inject a small amount of water into the airline. The injection pump and plumbing are extremely dangerous if failure occurs because they are subjected to maximum pressure.
CAUTION

Do not exceed the maximum air-pressure ratings of percussion drills.

WARNING

Rapid expansion of compressed air from bursting hoses and loose connections may cause injury. Only use replacement parts in the air system that the appropriate technical manuals recommend.

d. Rotation. As drilling progresses, adjust the bit rotation to the penetration rate. As the hole deepens, the bit should make one revolution equal to the length of exposure of the carbide buttons in the bit (about 1/3-inch). The rule of thumb is that the rotation rate (in rpm) should approximately equal the penetration rate in feet per hour. The rotation rate for percussion drilling is slower than for rotary drilling. For percussion drilling to function at maximum proficiency, the rotation must be constant. As the piston strikes the bit shank (about 1,200 blows per minute at maximum air pressure), the constant rotation allows the bit buttons to chip continuously at new rock. If the rotation rate is not constant (stops and jumps), the buttons hammer several times in one place before jumping to new rock. Erratic rotation produces variable sized chips, which are harder to clean from the hole. Erratic rotation also causes the buttons to penetrate too deep, increasing drag on rotation and excessive wear and button breakage.

There are two main causes for erratic rotation; hydraulic top-head-drives and borehole wall friction. Top-head-drive rigs rotate the drill string with a hydraulic motor. Even when tremendous torque is applied, a hydraulic system does not produce positive movement and reacts to drag or resistance to cause drill string rotation. The hydraulic top-head-drive rig is highly susceptible to erratic rotation. The primary force resisting rotation is weight on the bit. If this weight is excessive, the hydraulic drive produces a series of pressure variations and the bit rotates in a sequence of starts and stops. Even with mechanical drive rotation, which is nearly a positive movement, drag on the drill bit causes twist in the drill string, resulting in erratic rotation of the bit. This occurrence is more pronounced in deep holes.

The secondary cause of erratic rotation is borehole wall friction. All friction between the borehole wall and the drill string cannot be eliminated. The more a borehole deviates, from being straight, the greater the friction. It is easy to visualize a distorted drill string caused by excessive top loading and how the distortion causes increased borehole wall friction. Other contributors to borehole wall frictional are: rock abusiveness, poor lubrication of the drill string (injected or natural-water condition), and poor cutting removal.

4. Adjusting to Variables. Economical and satisfactory drilling, using the down-hole percussion drill, requires fine tuning of the variables. Efficiency is directly proportional to the air pressure delivered to the drill. Operating at the maximum air pressure should be the constant. The bit load, ideally a bottom string load, should exceed the maximum load required for the drill in order for the load to be properly adjusted by increasing hold back with the drill rig. Do not overload the bottom string because the drill string weight increases as the depth increases. Do not overload the hoisting capacity of the rig. Adjust the rotation speed to the penetration rate and use the constancy of the rotation to regulate weight on the bit.

Air blows the rock chips from under the drill bit on up the annulus to the surface. Since air has no effective viscosity or density to float the chips, removal is a function of the velocity of the returning air. A minimum velocity of 3,000 to 4,000 fpm is necessary. Larger diameter drill pipe reduces the area of the
annulus, which effectively increases the velocity of a fixed air volume. If the required up-hole velocity is not achievable, add foam to help remove cuttings.

Effectively removing cuttings as drilling progresses is critical. When the drill bit is extended in the splines, to the open position, the maximum volume of air passes through the drill. Cuttings may not be removed efficiently from the hole, resulting in an accumulation of cuttings around the drill. Accumulation may increase when compressor capacity is insufficient to maintain maximum pressure while drilling. This condition may be signaled by the drill sticking, which retards downward movement and affects bit load and drilling energy. The sound of the drill indicates this problem. Apparent change in the air return, cuttings returned from the annulus, and other indicators learned from experience also indicate an accumulation problem.

Detrimental effects of inefficient cuttings removal include reduced penetration rate, damage to the formation by fracturing, induced instability in the hole wall, damage to or even loss of drilling equipment, and loss of the borehole. Accumulation may be caused by insufficient drilling air volume, a percussion drill not suited for the hole, a sudden influx of groundwater, or too rapid a penetration rate (large load of cuttings). The alert driller senses a problem before it seriously affects the operation. Keep the hole and blow out all cuttings before shutting off the air to add another rod. By raising the drill slightly, the bit is extended in the splines (open piston), the percussive action stops, drill bit penetration (production of cuttings) stops, and maximum air passes through the drill to clear cuttings from the borehole. The alert and efficient operator uses this technique as conditions dictate.

The down-hole percussion drill is designed to operate in extremely unfavorable conditions. The service life is dependent on proper care. Lubricate the drill during operation. Use the manufacturer’s recommended injection of a minimum of one quart of rock drill oil during each hour of drilling. During drilling, the WDS is oiled with an in-line oiler plumbed into the drilling air line. Water injection into the air line is common and is not detrimental to the lubrication process. Drill rigs used for pneumatic drilling are equipped with a small, positive displacement pump (injection pump). Injecting water is helpful because it reduces dust at the surface, improves cuttings removal, and stabilizes the borehole wall. A water injection of 2 to 5 gpm is satisfactory. Adjust injection rates to the specific material drilled. Water injection improves lubrication of the drill string, provides some cooling of the compressed air and drill system, and is beneficial for rock drilling.

When the drill is removed from the borehole, break it down, inspect it, clean it, and repair it, as necessary. Oil all machined surfaces and lubricate threads with tool-joint compound before returning the drill to the borehole or to storage. Often a drill is left idle in the hole for an extended period. If this occurs, lubricate the drill. Lift the drill off the bottom, close the water injection valve, blow air through the hammer, and add oil (1 to 2 quarts) to circulate and lubricate the surfaces. Reasonable service and care improve the life of the drill.

### 4.4 DRILLING INFORMATION

1. **Driller’s Log.** Prepare a driller’s log for every well drilled. The log contains data, such as water-bearing-strata information, used to locate and drill a well. Figure 4-23 (DD Form 2678) and Figure 4-24 (DD Form 2679) provide examples of a well driller’s log and piping and casing log respectively. These forms are in the back of this manual for reproduction and use. Items to record in the remarks section of the well driller’s log could include the following:

   a. Changes in circulation, color, and consistency of drilling fluid.

   b. Observations of the cuttings carried to the surface.

   c. Depth to material contacts.

   d. Size and apparent classification of the cuttings.
e. Fluid loss or gain.

f. Penetration rate.

g. Soil description (fine or course, clay or sand).

2. **Soil Sampling.** Try to obtain good material samples and log the depth from which the samples came. Cuttings continuously wash to the surface during drilling. These cuttings are useful, but are not the samples mentioned above. To collect a specific cutting sample, stop drilling and continue fluid circulation to wash most of the cuttings from the hole. When the hole is clean, advance the bit through the sampling interval and stop. Collect samples from the fluid of the drilled section and resume drilling after taking samples. Although redundant sampling impacts drilling progress, worthwhile information is obtained and must be done irrespective to schedule impact. Field modifications of well design are often required, especially when subsurface information is sparse. In most cases, the changes made during well drilling are minor. For example, placing a screen a few ft higher or lower to match the position of the most gravelly part of an aquifer or adjusting a grout interval to match an impermeable layer above the aquifer.
## WELL DRILLER'S LOG

### 1. PROJECT TITLE OR WELL NUMBER
Stone Hill #25

### 2. LOCATION
Fort Leonard Wood, Mo
- **a. COUNTRY**: US
- **b. MAP**: Big Piney
- **c. SHEET NUMBER**: 7559 II
- **d. COORDINATES**: NG 79557649

### 4a. NAME OF DRILLER(S)
- Harold Johnson
- Anthony Price

### 4b. INITIALS
- HJ
- AP

### 5. DRILLING DETAILS

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<th>VISCOITY (d.)</th>
<th>TYPE OF FORMATION (e.)</th>
<th>BIT &amp; TYPE (f.)</th>
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<td>drag</td>
<td>(pH 7) neutral</td>
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**Note:** Sample Piping and Casing Log (Sheet 1 of 2)
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CHAPTER 5

Well-Installation Procedures

5.1 SETTING CASING

In rotary-drilled water wells, the surface casing may be set in the borehole after drilling is finished. However, the casing must be set and grouted near the surface. This prevents the upper portion of the borehole from caving in.

For water wells drilled in rock aquifers, the casing may be placed through the unconsolidated strata and into the rock to get a tight seal. However, this method does not ensure a tight seal. Improvement to the seal is accomplished by using the following procedures:

- Step 1. Drill a borehole about 10 ft into the rock.
- Step 2. Flush the hole with clean water.
- Step 3. Fill the rock interval with grout, and immediately set the casing into the hole. Let the grout set around the bottom of the casing.
- Step 4. Drill through the grout, plug in the lower casing, and progress into the aquifer.
- Step 5. Complete an open-hole well or install a smaller casing and screen inside the outer casing.

Note: Grout cannot be poured through drilling fluid to properly seal the casing.

5.2 SELECTING CASING

Well casing is plastic, wrought iron, alloyed or unalloyed steel, or ingot iron. Well-completion kits have either plastic (see Figure 5-1) or steel casing. It is important to understand the properties of different material since availability factors into usage decisions. When selecting the casing, consider the stress factor during the installation process, the corrosive element of the water, and the subsurface formation.

If casings other than those in the well-completion kits are used, the weight per ft of pipe must be specified. The tables in A100-66, American Water Works Association (AWWA), Standard for Deep Wells, present data on the steel and wrought-iron pipes used as permanent well casings. Joints for permanent casings should have threaded couplings or should be welded or cemented so they are watertight from the bottom of the casing to a point above ground. This precaution prevents contaminated surface water and groundwater from entering the system. Figure 5-2 lists hole diameters for various sizes and types of well casings.

Note: When using polyvinyl chloride (PVC) casing do not store in direct sunlight.

5.3 INSTALLING CASING

The list below describes various methods for installing casing:
1. **Open-Hole Method.** With this method, install casing using the following procedures:

- **Step 1.** Clean the borehole by allowing the fluid to circulate with the drill bit close to the bottom so cuttings come to the surface. The borehole may be carried deeper than necessary so that if any material caves in, the material fills the extra space below the casing depth.

- **Step 2.** Attach a coupling to the top of the casing. Suspend the casing by either attaching a hoisting plug to the coupling, using a sub (adapter) if necessary, or by placing a casing elevator or a pipe clamp around the casing under the coupling.

- **Step 3.** Lower the first length of casing until the coupling, casing elevator, or pipe clamp rests either on the rotary table or on another support placed around the casing. If lifting with a sub, unscrew the sub on the first length of casing and attach it to the second length of casing. If lifting by elevators or pipe clamps, release the elevator bails from the casing in the hole, and attach it to another elevator casing or pipe clamp on the second length of casing. Lift it into position, and screw it into the coupling of the first casing length (lightly coat the threads of the casing and coupling with a thin oil). Screw the lengths tightly together to prevent leaking. Remove the elevator or other support from the casing in the hole and lower the string that is supported by the uppermost coupling.

- **Step 4.** Repeat the procedure for each casing length installed. If a cave-in occurs, attach a swivel to the casing with a sub and circulate the drilling fluid through the casing to flush out the hole and wash the casing down. After the casing is set on the bottom of the hole, drill through the casing into the aquifer.

2. **Single-String Method.** With this method, install the casing and screen (that have been joined) in a single assembly. Refer to Paragraph 5.6 for additional details on screen installation.

3. **Wash-In Method (Jetted Wells).** With this method, the borehole is advanced for an expedient jetted-well construction. The water source is attached to the casing and screening. A pointed bottom cap allows high pressure water or air to be forced through it to move cuttings as casing string is inserted in hole (similar to forcing a water hose into ground). This method is ideal for soft, sandy material and shallow wells.

4. **Driven Method (Driven Wells).** Install the casing as with the borehole, the cable-tool, or the driven-point well method. This method is not a military standard and requires special attachments. The drill bit advances just ahead of the casing and both go into the ground at the same time.
<table>
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<td>12.090</td>
<td>0.330</td>
<td>8.4</td>
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**Figure 5-2. Well Casing Hole Diameters**
5. **Uncased-Interval Method.** In rock, the lower portion of the borehole is normally left uncased because water emerges from irregular functions in the borehole wall. Therefore, for the well to function properly, care is necessary when locating the bottom of the cased portion in relation to any impermeable zone. Once the depth is established, drill down and set the casing and then drill a smaller hole to full depth and proceed with development.

### 5.4 GROUTING AND SEALING CASING

Once grout is mixed, it starts to set. Therefore, place the mixture immediately after mixing it. The grout must be freshly mixed continuously to meet requirements. Portland cement meets most grouting requirements (a quick-hardening cement may be used to save time). For proper consistency, use no more than 6 gallons of water per 94-pound sack of cement. If a large amount of grout is necessary, add 1 cubic ft of fine or medium sand for each sack of cement. Add a few lbs of bentonite or hydrated lime per sack of cement for a better flow. For small jobs, and if no equipment is available, use a 55-gallon steel drum as a mixing tank. Put 20 to 24 gallons of water in the barrel and slowly add 4 bags of cement while stirring or jetting the water. Use as many mixing barrels as the job requires. If a concrete mixer is available, mix batches and dump them into a storage vat for future use.

Grout may be forced into place using pumps or air or water pressure. In some cases, use of a dump bailer is possible. If the tremie method is used, one or more strings of pipe with small diameters is necessary. Other equipment necessary are a mixing tank, hoses, and a feed hopper. The list below describes various methods for placing grout:

1. **Dump-Bailer Method.** With this method, grout is simply placed and with a minimum amount of equipment. On the dump-bailer, the bottom valve opens and the operator unloads grout at a specified location. This method works best for grouting only the lower portion of the casing. Use the following procedures to place grout:

   - **Step 1.** Run the casing in the hole and mix enough grout to fill the lower 20 to 40 ft of the hole (a quick method of mixing the grout is to put the required amount of water in a barrel and circulate the water, using a high-pressure jet while adding cement).

   - **Step 2.** Place the grout inside the casing with a dump-bailer.

   - **Step 3.** Lift the string of casing 20 to 40 ft off the bottom, depending on the amount of grout placed. The lower end of the casing should be below the top of the grout. Fill the casing with water and cap the top.

   - **Step 4.** Lower the casing to the bottom of the hole to force most of the grout up the annular space outside of the casing. Do not uncap the top of the casing until the grout is set.

   - **Step 5.** Drill through the cement that has hardened in the lower end of the casing and continue drilling to the required depth (green cement increases the viscosity of the drilling mud).

   If difficulty is anticipated in filling the casing with water when it is lifted in the borehole, add water on top of the grout without lifting the casing. Calculate the volume of grout in the casing. Fill the casing to the top with water. Connect a pump to force in additional water. Pump water into the casing, measuring the volume pumped, until a quantity equal to the volume of grout is put in. This forces all or most of the grout out of the lower end of the casing. Place a wad of burlap on top of the grout before filling the casing with water to keep the fluids separated.

2. **Inside-Tremie Method.** With this method, place the grout in the bottom of the hole through a tremie pipe that is set inside the casing (see Figure 5-3). The grout either descends naturally or a pump is necessary to force it through the pipe. Make sure that the tremie pipe is at least 1-inch in diameter. With this method and any other method where grout is placed inside the casing, make sure that water or drilling fluid circulates up and around the casing before starting to grout. To check this, cap the casing and pump in water. If the water comes to the surface outside the casing, start grouting. Use the following procedures to complete the tremie method:
Figure 5-3. Inside-Tremie Grouting Method

- Step 1. Continue pouring grout until it appears at the surface around the casing. Once the grout reaches the desired depth, it fills the space around the outside of the casing.

- Step 2. Suspend the casing about 2-ft above the bottom of the borehole during the operation. Once the grout is in place, lower and seat the casing in a permanent position. Remove and clean the tremie pipe. The check valve prevents the grout from moving back into the casing.

- Step 3. The grout should set and harden in about 24 to 72 hours, depending on the cement used. Drill out the packer and continue drilling the well below the grouted casing.

3. **Outside-Tremie Method.** With this method, use a tremie pipe to deliver grouting outside the casing. This method is not recommended for depths greater than 100 ft. Only use this method if the space between the casing and the borehole wall is large enough to contain a 1-inch tremie pipe. Use the following procedures to complete grouting using this method:

- Step 1. Lower the pipe to the bottom. Make sure that the lower end of the casing is tightly seated at the bottom of the borehole.
• Step 2. Mix a sufficient quantity of grout and pump it through the tremie pipe or let it descend naturally (see Figure 5-4). As the grout is placed, lift the tremie pipe slowly, but keep the lower end submerged in the grout.

• Step 3. Fill the casing with water as the grout is placed to balance the fluid pressure inside and outside the casing. Doing so prevents grout from leaking under the bottom of the casing.

Grouting near the surface is accomplished quickly using a tremie or by dumping the grout in the hole around the casing and puddling it with pipe lengths. However, this procedure only provides a surface seal around the casing and cannot be used as a normal grouting method.

**CAUTION**

GROUTING AROUND PVC PIPE MAY CAUSE EXCESS PRESSURE THAT MAY COLLAPSE THE PIPING.

### 5.5 SELECTING SCREENS

The military uses continuous-slot screens (see Figure 5-5) when drilling wells using the rotary method. Screens are fabricated by winding triangular sections around a skeleton of longitudinal rods. Join the triangular sections and rods securely wherever they cross. The screens are constructed of either PVC or stainless steel and are packed in the well-completion kits. Some important factors to remember when selecting screens are that they:

![Figure 5-4. Outside-Tremie Grouting Method](image)
1. Must produce a sand-free well of less than 2 ppm.

2. Should prevent minimum head loss.

3. Should be of a commercial grade (screen sizes are in increments of 0.005 inch).

4. Should lend themselves well to development (allow for a two-way flow).

The list below describes selection and sizing of screens:

1. **Types.**

   a. **PVC Screens.** These screens must be at least 8-inches in diameter. Continuous-slot PVC screens are in the 600-ft well-completion kits packed in boxes containing four 20-inch-long sections that are joinable (see Figure 5-6). The kits contain enough sections to assemble up to 50 ft of continuous-slot, 8-inch well screen.

   The PVC casings may be used to construct an alternative screen in the field by sawing or milling horizontal slots in sections of the 20-ft-long casing (cut six rows of slots down the casing). The slots are a ½-inch apart at a width of 0.025-inches. The following lists saws and approximate slot sizes:

   (1) Hacksaw, about 0.035 inches.
   
   (2) Handsaw, 0.050 to 0.080 inches.
   
   (3) Circular saw, 0.100 to 0.125 inches.

   These makeshift screens are not as efficient as the continuous-slot screens because of the relatively low open area per ft of screen. However, these screens may be necessary if the kit contains an insufficient number of continuous-slot screens. The alternative screens are the same as the casing sections. Place the screens intermittently up the well if more than one aquifer or water-bearing strata is screened. If multiple intervals are screened, place gravel packs around the screens and backfill between the screens. If sufficient gravel-pack material is available, use it continuously above the top of the screen.

   b. **Stainless-Steel Screens.** These screens are usually 6 inches in diameter and come in 9- and 20-ft sections. The sections are joinable to make longer pieces. Most stocked screens have 0.025-inch openings that are suitable for medium-sand formations. Screens with other slot openings are available and may be needed for special installations. Various end fittings are available to accommodate different installation methods. See Paragraph 5.6 for uses of these end fittings.
c. **Pipe-Base screen.** This screen is made by wrapping a trapezoidal-shaped wire around a pipe base that has drilling holes evenly spaced. A pipe-base screen is strong and suitable for deep wells. The screen has two sets of openings; outer openings are between adjacent turns of the wrapping wire and inner openings are the holes drilled in the pipe base. The percentage of open area per ft of screen (usually low) governs the efficiency of the screen. These screens come in 3- and 4-inch pipe bases for field OPS.

2. **Lengths.** Screen length should not exceed the thickness of thin aquifers. Screen the bottom third of unconfined aquifers and 75 to 80 percent of confined aquifers. However, for interlayered fine and coarse beds, consider the thickness of the coarse strata when determining screen length. Set the screen in the coarse strata. When choosing slot sizes, consider the percentage of the open area or intake area of the well screen to determine length. Use the following calculations to determine the amount of screen to use during drilling OPS:

a. **Surface Area.**

\[ SA = \pi (OD) \]  

where:

\[ SA = \text{surface area, in inches per ft.} \]

\[ OD = \text{outside diameter of the screen, in inches.} \]

b. **Open Area.**

\[ OA = \frac{SO}{SO + WD} \times 100 \]

where:

\[ OA = \text{open area as a percentage.} \]

\[ SO = \text{slot opening, in inches.} \]
\( WD = \text{wire diameter, in inches.} \)

c. Total Area.
\[
TA = (SA)(OA)
\]
where:
\( TA = \text{total area, in square inches.} \)
\( SA = \text{surface area, in inches per ft.} \)
\( OA = \text{open area, as a percentage.} \)

d. Transmitting Capacity.
\[
TC = (TA)^{0.31}
\]
where:
\( TC = \text{transmitting capacity, in \text{gpm per ft of screen} (based on one-tenth ft per minute of velocity).} \)
\( TA = \text{total area, in square inches.} \)

e. Screen Length.
\[
SL = \frac{PR}{TC}
\]
where:
\( SL = \text{screen length required, in linear ft.} \)
\( PR = \text{pumping requirement, in \text{gpm}.} \)
\( TC = \text{transmitting capacity, in \text{gpm}.} \)

The following example uses the above equations to determine the amount of 12-inch screen required at one-tenth ft per minute of velocity with a slot opening of 0.040-inches, a wire size of 0.092 inch, and a pumping requirement of 800 gpm:

\[
SA = \pi(OD)(12) = (3.14)(12)(12) = 452.16 \text{ square inches.}
\]
\[
OA = \frac{SO}{SO + WD} \times 100 = \frac{0.040}{0.040 + 0.092} \times 100 = 30.30 \text{ percent.}
\]
\[
TA = (SA)(OA) = (452.16)(0.3030) = 137 \text{ square inches.}
\]
\[
TC = (TA)^{0.31} = (137)(0.31) = 42.47 \text{ gpm.}
\]
\[
SL = \frac{PR}{TC} = \frac{800}{42.47} = 18.83 \text{ linear feet.}
\]

3. **Diameters.** The diameter of the well screen usually corresponds to the diameter of the well casing. The following considerations are also germane:

a. Increasing the screen diameter increases the yield or capacity of a well. The increase is not proportional.
b. Doubling the diameter of a well screen increases the capacity of the well by about 10 percent.

c. Using a larger diameter screen if the aquifer is thin or the pump is large facilitates better performance.

d. Using a long screen with a smaller diameter in a thick aquifer facilitates better performance.

e. Increasing the length, not the diameter, of the screen increases the yield of a well in a thick aquifer.

4. **Slot Sizes.** The function of slot size in well construction is important. When possible, choose the screen slot size to fit the gradation or grain sizes of the aquifer. Sand and gravel interaction greatly affects the development of the formation around the screen. Small openings limit well yield. Also, small slot sizes produce high velocity in the water passing through the screen. In time, scale or incrustation tends to form on the screen. If the openings are too large, the well may require more development than usual or it may not be able to clear the well of sand.

Screen slots that are sized to retain the coarsest one-third to one-half of sand or gravel of the aquifer work best in a naturally developed well. About two-thirds of the sand in the layer behind the screen should pass through the slots. A screen set across both coarse and fine strata may need sections with different slot sizes. If the screen requires artificial gravel packing, make sure the slot openings correspond to the size of the gravel selected. Screen openings that retain about nine tenths of the gravel works best.

5.6 INSTALLING SCREEN

Several methods are possible to install screens in rotary-drilled wells. To set well screens, use the screen hook and casing elevators. The hook engages a bail in the bottom of the screen to suspend the screen on either the sand line or hoist line while lowering the screen into the well (see Figure 5-7). Do not pull the screen with the hook after the formation has closed in around the screen. If installing a screen, use the telescoping method and seal the casing (rubber or neoprene packers are necessary). All screen-setting methods require accurate and complete measurements of pipe, screen, cable length, and hole depth. The list below describes screen installation methods:

1. **Single-String Method.** With this method, install the casing and screen as one assembly. Figure 5-8 shows a single-string assembly equipped with fittings for the washdown method. The washdown fittings may be omitted if the hole stays open at the bottom. Use the following procedures to install the assembly:

   - Step 1. Attach couplings to the top of the casing and screen section. Install a sand trap to the bottom of the string.
   - Step 2. After running the entire string into the borehole, use casing elevators to carry most of the weight of the string until the formation collapses in around the screen.
   - Step 3. Run the drill pipe inside the casing to the bottom of the screen, and pump water into the well to displace the drilling fluid.
   - Step 4. Raise and lower the drill pipe to wash the full length of the screen.
   - Step 5. Wait for the formation to settle around the screen. Proceed with well completion and development.

For deep wells and wells requiring surface casing, use the following modified telescoping procedure:

   - Step 1. Grout the surface casing in the borehole before drilling the well to the final depth.
Figure 5-7. Screen-Hook Installation Method

Figure 5-8. Single-String Assembly
• Step 2. Use the single-string method inside the surface casing, while bringing the inner casing to the surface.

• Step 3. After placing the gravel pack around the screen and impervious backfill on top of the gravel, grout the entire annulus between the inner and outer casing to the surface.

A disadvantage of the single-string method is the weight of a long string of casing on top of the screen. When the screen touches bottom, it becomes a loaded column that easily buckles because of its slenderness. When the screen reaches the correct depth, buckling is preventable by supporting the screen on casing elevators until the formation material collapses around the screen and supports it laterally.

2. **Pull-Back Method.** This is another method of installing a telescoping screen. It is used when the drilled material is so loose, surface casing is needed to finish bottom hole depth. Use the following procedures for this method:

• Step 1. Sink the well casing to the full depth of the well and clean out the hole to the bottom of the pipe with the bailer.

• Step 2. Assemble the closed bail plug in the bottom of the screen and screw one or more packers to the top of the bail plug.

• Step 3. Lower the screen inside the well casing using the sand line. After setting the screen on the bottom, pull the casing back far enough to expose the screen in the aquifer and to a position where the packer is still inside the casing.

• Step 4. Use a casing ring and slip with two hydraulic jacks to pull the pipe. If the screen moves upward as the pipe is pulled, lower the drill bit or another tool inside the screen to hold the screen down.

• Step 5. Hold the casing with pipe clamps until either the hole caves around the casing and grips the pipe or until grout is placed and sets around the casing, after pulling the casing to its permanent position.

• Step 6. Bail out the drilling mud so that the sand and gravel of the formation closes in around the screen.

3. **Open-Hole Method.** Use this method to install a telescoping screen when the depth and thickness of the aquifer have been predetermined. Use the following procedures for this method:

• Step 1. Sink the well casing into the aquifer to a depth slightly below the desired position from the top of the well screen. Fix the casing in place by grouting or other means.

• Step 2. Mix drilling mud and fill the casing. Using a bit that passes through the casing, drilling into the aquifer below the casing to make room for the length of well screen to be exposed.

• Step 3. Lower the screen into position, ensuring that the rubber or neoprene packer remains inside the casing near its lower end when the screen is on the bottom. If the hole is too deep, drop gravel into the hole to the correct height.

Use the closed bail plug and the packer top-end fittings to support the screen and sand trap (see Figure 5-9). With this method, the diameter of the screen must be smaller than the casing, since the hole drilled for the screen is no larger than the ID of the casing. Also, make sure that the packer fitting at the top of the screen is the proper size to seal inside the casing. The drilling mud must be heavy and thick to prevent the open borehole from caving in and the mud must be completely removed from the aquifer during development.

4. **Washdown Method.** This method works best if the aquifer is composed of fine to coarse sand with little or no gravel. The screen fittings necessary for this method are a washdown or self-closing bottom. Figure 5-10 shows a fitting when using a telescoping method to set the screen through the casing. Set the casing
from the surface to slightly below the depth where the top of the screen is installed. Screw a section of wash pipe into the left-hand female thread of the self-closing bottom and attach the bottom to the screen or sand trap with the wash pipe projecting through the screen. Lift the entire assembly by the wash pipe and lower the screen inside the casing. Add sections of wash pipe until the bottom of the screen is near the lower end of the casing. Use the following procedures for the washdown method:

- **Step 1.** Connect the top of the wash pipe to the kelly and start the mud pump. Circulate water (not drilling mud) down the wash pipe.

- **Step 2.** Let the screen move down as circulation continues and material washes. Take measurements and stop the descent of the screen when the packer is near the lower end of the casing. If drilling mud is still washing out of the well, continue pumping water until most of the mud is displaced.

- **Step 3.** Stop the pump and let the aquifer close in around the screen. When the formation develops friction on the outer surface of the screen, turn the entire string of wash pipe to the right to unscrew the left-hand joint at the bottom.

- **Step 4.** When the wash pipe is free, pump in more water. Raise and lower the string several times so that the lower end travels the full length of the screen. This action washes out more drilling mud and some fine sand from the formation.

- **Step 5.** Start development work, remove the wash pipe, and continue the development work.
5. **Bail-Down Method.** With this method, special end fittings are necessary for the screen. Figure 5-11 shows an assembled bail-down shoe in the bottom of the screen. The bail-down shoe has a special nipple that has right- and left-hand threads and a coupling with right- and left-hand threads. Figure 5-12 shows a shoe with a guide pipe that extends below the screen. Use the following procedures for the bail-down operation:

- **Step 1.** Start the operation after the well casing is sunk to its permanent position. The casing’s lower end should be slightly below where the top of the screen is installed.

- **Step 2.** Assemble the bail-down shoe, special nipple, and special coupling in the bottom of the screen.

- **Step 3.** Screw a length of premeasured pipe into the right-hand half of the special coupling. This pipe, that extends up through the screen is called the bailing pipe or conductor pipe.

- **Step 4.** Screw one or more packers to the top of the screen.

- **Step 5.** Lift the whole assembly by the bailing pipe and lower the screen inside the well casing. Add lengths of bailing pipe as the screen descends until it reaches the bottom of the borehole.

- **Step 6.** Mark off the length of the screen on the bailing pipe that projects above the casing, using the top of the casing as the reference measuring point. Run a bailer or sand pump inside the bailing pipe and start bailing sand from below the shoe.

- **Step 7.** As sand is removed from below the shoe by the bailer, the combined weight of the screen and the string of bailing pipe cause the screen to move downward. Attach additional weights to the bailing pipe, if necessary.
• Step 8. Monitor the progress of the work carefully and stop the operation when the screen reaches the desired depth. The packer should be near the lower end of the casing, but still inside the casing. Accurate measurements avoids sinking the screen too far.

• Step 9. Drop a weighted and tapered wooden plug (see Figure 5-12) through the bailing pipe to plug the special nipple on the bail-down shoe. When the plug is in place, unscrew the left-hand threaded joint at the upper end of the nipple by turning the entire string of bailing pipe to the right. Remove the bailing pipe and proceed with well development.

If a different type of bail-down shoe is used, the left-hand threaded connection for the bailing pipe may be in the shoe opening or the packer fitting at the top of the screen. In either case, use the same procedures as above to bail-down, plug the bottom, and remove the bailing pipe.
Under certain conditions, bail-down of a well screen is accomplished without using a bail-down shoe. The bailing pipe is not connected to the screen. The pipe's lower end is fit with a flange or coupling large enough to press on the packer at the top of the screen. The weight of the bailing pipe rests on the screen. Fit the lower end of the screen with an open ring or a short piece of pipe. Be very careful when using this method because the screen is not connected to the bailing pipe and the screen’s movement is uncontrollable from the surface. Careful measurements prevent sinking the screen too far. This method should be limited to fairly short screens. Plug the bottom of the screen by putting a small bag of dry concrete mix in the bottom and tapping the concrete lightly with the drill bit or another tool.

5.7 PLACING GRAVEL

The most important criteria for gravel pack (artificial sand filters) are compatible grain sizes and screen slot openings. Grading should be in proper relation to the grading of the sand in the aquifer. Trouble may arise if the gravel is too coarse. Coarse, uniformly graded filter sand (about 1/8-inch) makes the best gravel pack for most fine-sand aquifers. Use fine gravel (1/4-inch maximum size) to pack aquifers consisting of medium or coarse sand. Use a screen with openings that cover about 90 percent of the gravel pack. The following is a field method for producing a filter material or gravel pack from a sand and gravel deposit for a medium sand aquifer:

- Step 1. Make two sieves with lumber. Cover one sieve with a 1/4- to 3/8-inch hardware cloth. Cover the other sieve with window screen.

  **Note**

  A layer of hardware cloth under the screen provides extra strength to the sieve.

- Step 2. Discard all material that does not go through the hardware cloth but that goes through the window screen. Save the materials that the screen retains for analysis and logging purposes.

The list below describes gravel placement methods:

1. **Open-Hole Placement.** Where drilling mud keeps the borehole open, install a gravel pack using the positive-placement method. This method is the most common and best suited to military field OPS. Use the following procedures for this placement method:

   - Step 1. Drill a large diameter borehole the full depth of the well.

   - Step 2. Set a smaller diameter screen and casing centered in the large diameter borehole.

   **Note**

   Basket-type centering guides work best.

   - Step 3. Fill the annular space around the screen with properly graded gravel.

   - Step 4. Fill the borehole with gravel well above the top of the screen. Gravel works downward as sand and silt are removed from the formation around the gravel pack by subsequent development.

Development work must be thorough when drilling the borehole using the rotary method because the mud cake on the borehole wall is sandwiched between the gravel pack and the face of the formation. Break up the mud cake and bring it up through the gravel into the well. Any mud cake not removed reduces the efficiency and yield of the completed well. To ensure that all of the mud cake is removed, limit the thickness of the gravel envelope around the screen to a few inches. A common mistake is to drill a very large borehole and use a small screen, making the gravel too thick for satisfactory results.
Another common mistake is to try and place gravel pack into a small annular space, such as 1-inch. The gravel pack usually bridges at a coupling and does not get down around the well screen. A 2-inch annular space is the minimum, although 3- to 5-inch spaces are best. Remember, the annular space is the difference between the outside of the casing and the wall of the borehole with the casing centered in the hole. In most cases, the OD of the couplings must also be considered.

2. **Tremie Placement.** A tremie pipe is appropriate when placing gravel-pack materials in shallow to moderately deep wells. The fine and coarse particles should not separate, as in the open-hole placement, when the aggregate settles through the drilling fluid in the well. Lower a string of 2-inch (or larger) pipe into the annular space between the inner and outer casings. Feed the gravel into the hopper at the top of the pipe. Feed water into the pipe with the gravel to avoid bridging the material in the pipe. The pipe rises as the gravel builds up around the well screen.

3. **Bail-Down Placement.** With this method, the gravel pack and screen are installed at the same time. Feed the gravel around the screen as it goes downward with the screen. The bail-down shoe used is somewhat larger than the screen so that gravel being added follows down and around as the screen sinks in the formation. Figure 5-13 shows this operation. Development work is an essential part of this method. Screen openings must be larger than the grain size of the aquifer so enough aquifer sand passes through and the gravel pack replaces the sand around the screen.

4. **Double-Casing Placement.** With this method, gravel is used and placed as a temporary outer casing (see Figure 5-14). It is used as another method when surface casing is required to complete final depth. The casing is pulled back as gravel is poured into the space. This method is somewhat similar to pull-back screen installation.

### 5.8 USING ALTERNATIVE METHODS

The list below describes alternative methods:

1. **Formation Stabilizer.** When a gravel pack is not used, a formation-stabilizer material helps prevent deterioration of the annular space outside the screen. Fine, loose strata may cave into that space, enter the screened interval, and degrade the well. The decision to use this material usually occurs during the well-construction process. In unstable formations, consider stabilizing wherever the annular space is more than 2 inches thick.

   Grain size is important since the aquifer is developed naturally and as much as half of the stabilizing material could flow through the screen. The grain size should average slightly coarser than that of the aquifer and should be well distributed. Use the following procedures when using formation stabilizer:

   - Step 1. Center the screen at its final position in the open section of the borehole, using a centralizer if needed.
   - Step 2. Place the stabilizer material by dumping and tamping it down the hole or by using a tremie. Raise the level of stabilizing material above the top of the screen and add additional material as development progresses.
   - Step 3. As the well is developed, the level of the stabilizing material drops as the material is pulled into the screen. This material must be replaced to maintain the level above the top of the screen.

2. **Unscreened Well.** In consolidated rock, the aquifer is usually tapped through numerous, irregularly spaced fractures. Once cleared of mud and rock fragments, the fractures stay open and the intake interval functions efficiently for a longtime (a screen is usually not needed in such a rock well). If an unscreened well design is used, particular attention must be paid to the location of the top of the unscreened intake interval and its relation to the position and thickness of any impermeable layer.
Figure 5-13. Bail-Down Placement

Bailing pipe

Gravel added as screen is bailed down

Outer casing

Inner casing

Bail-down shoe with cone bottom
Figure 5-14. Double-Casing, Gravel-Pack Placement
CHAPTER 6
Well-Completion Procedures

Note
This chapter implements STANAG 2885 ENGR (Edition 4).

6.1 WELL DEVELOPMENT

Figure 6-1 describes different well development methods and some characteristics of each method. All methods are
designed to produce a stable flow condition. The list below describes well development methods in more detail:

1. Jetting Method. This backwashing method is an effective way to remove caked drilling mud from the
borehole wall by lowering a jetting tool inside the screen. However, its primary disadvantage in military
field OPS is that it requires a large supply of water. Use the following procedures for this method:
   • Step 1. Attach the jetting tool (in the well-completion kit) to the bottom of the drill string (see Figure
     6-2).
   • Step 2. Use the string to lower this tool into the screen.
   • Step 3. Connect the upper end of the pipe to the kelly or the discharge side of the mud pump.
   • Step 4. Pump water into the screen and rotate the jetting tool slowly so that the horizontal jets of water
     wash out through the screen openings.
   • Step 5. Raise the string of pipe gradually and continue rotating to backwash the entire surface of the
     screen. If possible, use a pump pressure of 100 psi.

   After covering the entire screen with the jetting tool, remove the tool. Remove the sand that has collected
   in the sand trap with a bailer. Repeat this process until the well stops producing sand. If a significant
   volume of material is removed during development, add more filter material around the screen to keep the
   top of the gravel pack above the top of the screen.

2. Pump-Surge Method. This backwashing technique involves pumping water to the surface and letting the
water run back into the well through the pump-column pipe using an airlift or a deep-well turbine pump
without a foot valve. See Chapter 7 for a discussion on pumps. Do not use the permanent well pump for
development (pumping sand could damage the pump). Use the following procedure for this method:
   • Step 1. Start the pump. As water comes to the surface, stop the pump to release the water. The power
     unit and starting equipment determine the starting and stopping action of the pump. The effect is to
     lower and raise the water level in the well intermittently through the screen openings. Periodically,
     pump the well to remove the sand brought in by surging.
   • Step 2. Remove the pump and bail out the material in the sand trap, after surging.
   • Step 3. Repeat the process until the well stops producing sand.
3. **Gravity-Outflow Method.** Backwashing by gravity outflow involves pouring water into the well rapidly to produce outflow through the screen openings. Inflow through the screen is then produced by bailing water from the well rapidly. This is a slow surging technique requiring several minutes to complete a cycle. If the static water level is high enough to permit pumping by suction lift, use a small centrifugal pump instead of the bailer to speed up the work. If there is room in the well casing, connect the discharge side of the pump to a string of small diameter pipe that is lowered into the well. The water added is pumped down inside the screen, creating a turbulence that helps develop the formation.

4. **Pressure-Pumping Method.** Occasionally, wells are backwashed by capping the casing and pumping water into the well under pressure. Water is forced outward through screen openings similar to the closed-well method of using compressed air for development (see Paragraph 6.1, item 6): Pressure pumping is an inefficient method because the desirable surging effect is difficult to produce. The casing seal must be tight in the borehole and prevent water from being forced up around the outside of the casing.

5. **Surge Block Method.** With this method, water is surged up and down in the casing with a surge block or plunger. A surge block is a solid plunger, swab, or a plunger equipped with or without a valve opening (see Figure 6-3). The valve-type plunger gives a lighter surging action than the solid type. Light surging is advantageous in developing tight formations. Therefore, start the surging process slowly and increase the force as the development proceeds. Be careful when working with wells using PVC pipe. The casing or well screen could collapse from vigorous surging action. Plugging the valve of the plunger changes it to a solid-type plunger that is used when greater surging force is necessary. Attach sufficient weight to the surge plunger to make it fall with the same speed on the downstroke as the drilling machine uses on the upstroke. The drill stem provides the weight required for the surge block. Use the following procedures for the surge block method:

<table>
<thead>
<tr>
<th>Method</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jetting</td>
<td>Effective on mud cake, needs abundant water</td>
</tr>
<tr>
<td>Pump-surge</td>
<td>Air-lift or deep-well pump needed</td>
</tr>
<tr>
<td>Gravity outflow</td>
<td>Simple and slow, bail or use small pump</td>
</tr>
<tr>
<td>Pressure pumping</td>
<td>Mostly inefficient, potential leakage outside casing</td>
</tr>
<tr>
<td>Surge block</td>
<td>Simple, effective, and slow</td>
</tr>
<tr>
<td>Compressed air (open)</td>
<td>Requires high submergence (head), needs a compressor</td>
</tr>
<tr>
<td>Compressed air (closed)</td>
<td>Potential leakage and disturbance outside casing, needs compressor and fittings</td>
</tr>
</tbody>
</table>

Figure 6-1. Well Development Methods

Figure 6-2. Jetting Tool on Bottom of Drill String
• Step 1. Lower the surge plunger into the well until the water is above the top of the screen. Keep the plunger a few ft above the screen so that it does not strike the screen while surging.

• Step 2. Start surging slowly and gradually increase the speed until the surge plunger rises and falls without slack. With a rotary rig, lift the plunger 3 or 4 ft before dropping it. When using the sand line, control movement by using the hoist brake and clutch.

• Step 3. Continue surging for several minutes. Pull the plunger out of the well and lower the bailer or sand pump into the screen. When the bailer rests on the sand that is pulled into the screen, check the depth of the sand by measuring it on the sand line. Bail all the sand out of the screen.

• Step 4. Repeat the surging operation and compare the quantity of sand with the first quantity. Bailout the sand.
• Step 5. Repeat surging and bailing until little or no sand is pulled into the well. Lengthen the period of surging as the quantity of sand removed decreases.

6. **Compressed-Air Method.** Compressed air provides rapid and effective development of wells, using an open- or closed-well method. The standard 350-cfm compressor works for developing most wells at a pressure of at least 100 psi. However, a higher pressure is preferable. The 250-cfm compressor pumps water by air lift from 100 to 150 gpm, depending on the submergence and size of the pipes uses. Figure 6-4 shows the recommended sizes of pipe and air lines and the pumping rates for various sizes of wells.

![WARNING]

If using PVC casing, ensure compressor psi output does not exceed breaking strength of casing material.

a. **Open-Well Method.** The surging cycle is established by pumping from the well with an air lift and by dropping the air pipe suddenly to cut off the pumping. This cycle discharges large bubbles of compressed air into the screen. The submergence ratio must be 60 percent. Submergence is the extent to which the air pipe is submerged in the water compared to the extent the pipe is between water and ground level. Work efficiency decreases rapidly as the submergence ratio drops below 60 percent. In deep wells with a considerable head and a low submergence ratio, some effective work is accomplished by shooting heads.

Figure 6-5 shows the proper method of placing the drop pipe and airline in the well. Use a hoist line to easily handle the drop pipe. Suspend the air pipe on the sand line. Fit a T pipe at the top of the drop pipe with a short discharge pipe at the side outlet. Wrap a sack around the air line where it enters the drop pipe to keep water from spraying around the top of the well. Discharge from the compressed air tank to the well should be the same size as or one size larger than the airline in the well. Connect a quick-opening valve in the line near the tank. A pressure hose, 15 ft long minimum is necessary for moving the drop pipe and air line up and down. Use the following procedures to start developing the well using this method:

• Step 1. Lower the drop pipe to within 2 ft of the bottom of the screen. Place the air line inside the drop pipe with its lower end 1 ft or more above the bottom of the drop line.

<table>
<thead>
<tr>
<th>Pumping Rate*</th>
<th>Size of Well Casing if Eductor Pipe is Used</th>
<th>Size of Eductor Pipe (or casing if no eductor pipe is used)</th>
<th>Minimum Size of Air Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>gpm</td>
<td>m³/day</td>
<td>in</td>
<td>mm</td>
</tr>
<tr>
<td>30 to 60</td>
<td>164 to 327</td>
<td>4</td>
<td>102 or larger</td>
</tr>
<tr>
<td>60 to 80</td>
<td>327 to 436</td>
<td>5</td>
<td>127 or larger</td>
</tr>
<tr>
<td>80 to 100</td>
<td>436 to 545</td>
<td>6</td>
<td>152 or larger</td>
</tr>
<tr>
<td>100 to 150</td>
<td>545 to 818</td>
<td>6</td>
<td>152 or larger</td>
</tr>
<tr>
<td>150 to 250</td>
<td>818 to 1,360</td>
<td>8</td>
<td>203 or larger</td>
</tr>
<tr>
<td>250 to 400</td>
<td>1,360 to 2,180</td>
<td>8</td>
<td>203 or larger</td>
</tr>
<tr>
<td>400 to 700</td>
<td>2,180 to 3,820</td>
<td>10</td>
<td>254 or larger</td>
</tr>
<tr>
<td>700 to 1,000</td>
<td>3,820 to 5,450</td>
<td>12</td>
<td>305 or larger</td>
</tr>
<tr>
<td>1,000 to 1,500</td>
<td>5,450 to 8,180</td>
<td>16</td>
<td>406 or larger</td>
</tr>
</tbody>
</table>

*Actual pumping rate is dependent on percent submergence.

Figure 6-4. Recommended Pipe Sizes for Air-Lift Pumping
Figure 6-5. Placing the Drop Pipe and Air Line in the Well

- Step 2. Let air enter into the airline and pump the well until the water appears to be free of sand. Start slowly. If all the water is suddenly removed, the casing may collapse in deeper wells, especially when using PVC pipe.

- Step 3. Close the valve between the tank and airline and pump the tank full of air to a pressure of 100 to 150 psi.

- Step 4. Lower the air line until it is about 1-ft below the drop pipe. Open the quick-opening valve so the air in the tank rushes with great force into the well until a brief, forceful head of water emerges or shoots from the casing and from the drop pipe.

- Step 5. Pull the airline back into the drop pipe immediately after the first heavy load of air shoots into the well. Doing so causes a reversal of flow in the drop pipe that effectively agitates the aquifer.

- Step 6. Let the well pump as an air lift for a short time and then shoot another head.

- Step 7. Repeat this process until no sand shows, indicating the completion of this stage of development.
• Step 8. Lift the drop pipe to a position 2-or 3-ft higher in the screen and follow the same procedure. This develops the entire length of the screen a few ft at a time.

• Step 9. Return the drop pipe to its original position and shoot one or two more heads.

• Step 10. To complete the development process and thoroughly clean out any loose sand, pull the air line up into the drop pipe, and use it as an air lift to pump the well.

b. Closed-Well Method. With this method, use compressed air to close the top of the well with a cap and arrange the equipment so air pressure builds up inside the casing to force water out through the screen openings (see Figure 6-6). Disadvantages with this method are:

(1) That valves and fittings may not be available for military field OPS.

(2) The danger of forcing water upward outside of the casing. This loosens the casing and could ruin the well by bringing clay down into the formation.

Use the following procedures to develop a well using this method:

• Step 1. Arrange the equipment as in Figure 6-6 and turn the three-way valve to deliver air down the air line, preferably with the air cock open. This pumps water out of the well through the discharge pipe.

Figure 6-6. Arranging Equipment to Build Up Air Pressure
• Step 2. When clear water emerges, cut off the air and let the water in the well regain its static level.

• Step 3. Listen to the air escaping through the air cock as the water rises in the casing to determine stability. Close the air cock and turn the three-way valve to direct the air supply down the bypass to the top of the well, forcing the water out of the casing and back through the screen. This technique agitates the sand and breaks down any bridging of sand grains. When the water is pushed to the bottom of the drop pipe, air escapes through the drop line. Air logging is prevented by keeping the drop pipe above the well screen.

• Step 4. Cut off the air supply and reopen the air cock so the water reaches the correct static level when the air is heard escaping from the discharge pipe or when the pressure stops increasing.

• Step 5. Turn the three-way valve and direct the air supply down the airline to pump the well.

• Step 6. Repeat this process until the well is thoroughly developed. Bailing the well after development is not usually required since the water velocity usually cleans out the sand from the well. However, if the well was not initially bailed out thoroughly, the bailing process is required to clean out the well.

**Note**

Be careful not to let the drill strike the bottom plug during well development, especially when using PVC pipe.

6.2 DISPERSION TREATMENT

Dispersing agents, mainly polyphosphates, when added to drilling fluid, backwashing, jetting water, or water standing in the well, counteract the tendency of mud to stick to sand grains. These agents are procured locally on an as-need basis. Baroid Industries produces barafos, a white, granular, sodium tripolyphosphate thinner and dispersant.

Chemicals such as sodium hexametaphosphate, sodium tripolyphosphate, and sodium septaphosphate are used to develop wells. Dispersants work effectively when applied at the rate of one-half lb of chemical to 100 gallons of water in the well. Let the mixture stand for about one hour before starting well development. Wetting agents, such as CON DET, increase the dispersion action of polyphosphates when added to the solution at a ratio of 1:100. Be careful when using the dispersion process because it could have an adverse reaction. The driller should make the decision whether to use dispersants.

6.3 ROCK DEVELOPMENT

Use this method to develop wells in rock formations. Good results are obtainable by combining jetting with airlift pumping from a limited zone isolated by inflatable packers. The objective is always to wash out fine cuttings, silt, and clay that have worked into the fissures, crevices, or pores of the rock during the drilling OPS. Openings that remain plugged reduce water flow into the well. Develop the well thoroughly to remove all obstructing material. When drilling through limestone formations, use acid to dissolve lime-like cementing material and to open up connections with joints or fissures beyond the borehole wall. However, such OPS are rare in military well drilling.

6.4 WELL PROTECTION AND TREATMENT

The list below describes well protection and treatment considerations:

1. *External Preparations*. Disinfect and protect the well drilling equipment before starting the borehole. Some other preventive measures are:

   a. Stopping surface contaminants from entering the well.
b. Ensuring that the drilling water’s quality is suitable.

c. Cleaning and disinfecting all drilling equipment before starting a new well.

d. Disinfecting the water used for drilling if a mud-based drilling fluid is used. If a synthetic drilling fluid is used, chlorinate the fluid. However, doing so breaks down the fluid and reduces its life.

e. Circumventing possible water-quality problems by stopping potentially harmful fittings and equipment from entering the borehole. Carefully check the list of the hardware and materials placed and left in the well.

Note

Well casings should extend no more than 12 inches above the pump-house floor on a final-grade elevation and not less than 12 inches above the normal anticipated flood level.

2. Sealing Casing. A well must be carefully protected from sewage and other contaminants that could migrate down the well column to the aquifer and well screen. Sources of pollution could be on the surface or in shallow perched water, unusable aquifers, and intermittently saturated beds. Carefully planning the well’s location could help avoid surface pollutants. However, subsurface contaminants may not be known until drilling starts. If this occurs, the location is no longer viable and the well is quickly sealed. Refer to Chapter 5 for details on sealing or grouting OPS and to STANAG 2885 ENGR (Edition 4) for sealing a North Atlantic Treaty Organization (NATO) well.

A rock well may be grouted from the lower end of the casing to the surface. Grout is placed between the inner and outer casings and around the inner casing in a portion of the drilled borehole below the outer casing. Make sure that overburden does not seal the borehole after setting the casing.

3. Disinfection. All newly constructed wells should be considered contaminated from the construction process and disinfected immediately after completion. Well-completion kits provide packages of a dry chlorinator for breaking down synthetic drilling fluids to disinfect the wells. Prepare a chlorine solution by:

- Step 1. Mixing 1 heaping tablespoon of calcium hypochlorite with water to make a thin paste. Break up all lumps.
- Step 2. Stirring mixture into 1 quart of water. Let the mixture stand a short time.
- Step 3. Pouring off the clear liquid.

The chlorine strength of the solution is about 1 percent. One quart of the liquid is enough to disinfect 1,000 gallons of water. Larger quantities of the solution may be prepared in the same proportion and, if placed in sealed containers (preferably glass), stored for several years without losing its effectiveness. When storing chlorine for long periods of time the solution needs to be stored in the dark since direct sunlight degrades the effectiveness of chlorine.

Estimate the volume of water standing in the well. Pour in the corresponding ratio of solution to gallons of water in the well (for safety, use less solution than too much solution since overchlorination could have long-term health effects if left uncorrected). Agitate the water in the well thoroughly and let it stand for several hours, preferably overnight. Flush the well to remove the entire disinfecting agent. Disinfect the well casing by returning chlorinated water to the well during the early stage of flushing and washing the walls.

For information on water purification and the storage, protection, monitoring, and testing of water, refer to MCWP 4-11.6, Petroleum and Water Logistics Operations; FM 21-10/MCRP 4-11.1D, Field Hygiene and Sanitation; and FM 10-52, Water Supply in Theaters of Operations.
4. **Cathodic Protection.** A sacrificial anode (see Figure 6-7) is the simplest method of protecting metal casing from corrosion. Connect a galvanically active metal bar, such as magnesium-coated wire, to the casing. Bury the anode bar near the casing below the water table. In this cell, ions flow to the casing through the groundwater. While the anode corrodes, the casing remains unaffected. Another method is to suspend cable (acting as the anode) into the well. The anode continues to operate and protect the casing until it is consumed (the anode is replaced as part of continuing maintenance).

5. **Well Head and Collar.** Use the well head in the well-completion kit; otherwise, extend the casing at least 1-ft above the general level of the surrounding surface. Seal the space around the outside of the casing by pouring a concrete platform around the casing at the surface (see Figure 6-8). To form a concrete platform, the following bill of materials (BOM) is necessary:

   a. Two 2-inch by 9-inch by 8-ft boards. Cut these in half for the walls.

   b. Eight 2-ft long No. 4 reinforcement bars for the corner stakes.

   c. One 4- by 4-ft wire mesh.

   d. About 0.5 cubic yards of concrete.

![Figure 6-7. Sacrificial Anode](image-url)
Use the following procedures to make the platform:

- Step 1. Clear the site with shovels.
- Step 2. Dig a 4-inch excavation.
- Step 3. Construct the form.
- Step 4. Place the wire mesh, snipping out the center for the casing pipe.
- Step 5. Mix and pour the concrete quickly.
- Step 6. Pull the wire mesh up through the concrete.
- Step 7. Screed with a 2-inch by 4-inch by 8-ft board (ensure minor slope away from casing).

**Note**

Mission requirements may cause variations in dimensions and design.

If a container is unavailable to mix the concrete, construct a mortar box using the following materials:

a. One 4-ft by 8-ft by 1/2-inch piece of plywood for the base.

b. Four 2-inch by 6-inch by 8-ft boards for the walls.

c. One 2-inch by 4-inch by 8-ft screed beam.

**Note**

When mixing concrete, add the water slowly. Use 5 gallons of water per sack of concrete. Mix it with a hoe and place the concrete quickly.

The upper surface of this slab and its immediate surroundings should be gently sloping so water drains away from the well. Place a drain around the outer edge of the slab and extend it to a discharge point that is far away from the well. A well with pipe casing should have a sanitary seal at the top that fills the space between the pump pipe and the well casing. This device consists of a bushing or packing gland that makes a watertight connection.
6.5 WELL-COMPLETION REPORT

Figure 6-9 is an example of a military water-well-completion summary report (DD Form 2680). This form is used to update the world-wide DOD WRDB after completion of all well drilling OPS. Fill out the form and send it to the address on the form. DD Form 2680 is in the back of this manual for reproduction and use.
# MILITARY WATER WELL COMPLETION SUMMARY REPORT

**TO**
US ARMY GEOGRAPHIC CENTER.
ATTN: HYDROLOGIC ANALYSIS TEAM
7701 TELEGRAPH ROAD
ALEXANDRIA, VA 22315
(703) 428-7869

**FROM**
COA 593rd Eng BN
Fort Leonard Wood, MO 65473
PHONE NUMBER (Include Area Code)
(314) 571-2100

**1. PROJECT TITLE OR WELL NUMBER**
Stone Hill

**2. DATE OF REPORT**
1 Oct 93

**3. USE**
- a. Military water supply
- b. Construction
- c. Humanitarian
- d. Other (Specify)

**4. LOCATION**
If Yes, complete (1) thru (4)

| a. Country | US |
| b. Map name/edition | Big Piney |
| c. Series/sheet number | 7559 II |
| d. Coordinates | NG 79557649 |
| e. Scale | 1:250,000 |

**5. TOP OF HOLE ELEVATION**
320' above sea level

**6. TOTAL HOLE DEPTH**
540'

**7. STATIC WATER LEVEL**

| a. Number feet | 200 |
| b. Below Grade | X |
| c. Above Grade | |
| d. Date Measured | 29 Sep 93 |

**8. TYPE OF DRILLING MACHINE**

| a. 600-ft WDS | X |
| b. ITWD | |
| c. CF-1S-5 | |
| d. Other (Specify) | X |

**9. DRILLING METHOD**

| a. Direct Rotary | |
| b. Reverse Rotary | |
| c. Air Rotary | |
| d. Other (Specify) | X |

**10. HOLE AND CASING DIAMETER** (Change inches to feet)

| a. Hole | |
| b. Casing | |

**11. COMPLETION KIT USED**

| a. Yes | X |
| b. No | |

**12. SCREENS**

| a. Completion Kit | |
| b. PVC | |
| c. Stainless Steel | |
| e. Depth 0 | X |

**13. GRAVEL PACK**

| a. Yes | X |
| b. No | |

**14. SANITARY SEAL**

| a. Grout Volume | 48 cu ft |
| b. Depth | 120 ft |

**15. WELL DEVELOPMENT**

| a. Method Jetted | |
| b. Date | 1 Sep 93 |

**16. PUMP**

| a. Standard | X |
| b. 600 feet | |
| c. 1500 feet | |
| d. Nonstandard Electric | |
| e. Hand-Pump type | |

**17. PUMPING TEST**

| a. Yes | X |
| b. No | |

**18. WELL-HOLD COMPLETION**

| a. Standard | X |
| b. Nonstandard (Specify) | |
| c. Height above ground (in feet) | 29 Sep 93 |

**19. WELL DISINFECTION**

| a. Super Chlorination | X |
| b. Other (Specify) | |

**20. GEOGRAPHIC DATA AVAILABLE**

| a. Yes | X |
| b. No | |

**21. COMPLETION KIT USED**

| a. Yes | X |
| b. No | |

**22. GEOGRAPHIC DATA AVAILABLE**

| a. Yes | X |
| b. No | |

**23. Water-Resource Overview**

| a. Yes | X |
| b. No | |

**24. OTHER (Specify)**

**25. DOWN-HOLE LOG**

| a. Attached | X |
| b. No | |

---

**Figure 6-9. Sample Well-Completion Summary Report (Sheet 1 of 2)**
21. OVERBURDEN MATERIALS
   a. Unconsolidated
   b. Sandstone
   c. Limestone
   d. Igneous
   e. Other (Specify)
      Silty, clayey, loam

22. AQUIFER MATERIALS
   a. Sand and Gravel
   b. Sandstone
   c. Limestone w/dolomite
   d. Igneous

23. MARKER BEDS (Describe)
   Chert/dolomite
   at 10 feet
   Sandstone
   at 320 feet
   at feet

24. WATER QUALITY
   a. Tested | X | (1) Yes | (2) No | (3) Date
   X | b. Fresh | c. Brackish | d. Saline

25. SKETCH OF LOCATION

26. REMARKS
   Well drilling permit issued through DEH Environmental office.
   Permit No. 478-9-91

27a. SUBMITTED BY (Type or print name)
   Marc B. Post

27b. GRADE/RANK
   E7/SPC

27c. UNIT
   593rd Eng BN

29. SIGNATURE OF PROJECT OFFICIAL

30. DATE OF SIGNATURE
   1 Oct 93

DD Form 2680, OCT 93 (BACK)

Figure 6-9. Sample Well-Completion Summary Report (Sheet 2 of 2)
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CHAPTER 7

Pumps

7.1 FUNDAMENTALS

The list below describes the fundamentals of pumps:

1. **Pump Types.** Pumps are classified according to use (for shallow or deep wells), design (variable or positive displacement), or method of operation (rotary, reciprocating, centrifugal, jet, or airlift). This chapter deals with shallow-well and deep-well pumps. Shallow-well pumps (suction-lift pumps) are normally installed above ground, on or near the top of the well casing. Deep-well pumps are installed in the well casing with the pump inlets submerged below the pumping level. These inlets are always under a positive head and do not require suction to move or pump the water.

2. **Selection Criteria.** Consider the following items when selecting a pump:
   a. Size of the well.
   b. Quantity of water to be pumped.
   c. Drawdown and pumping levels.
   d. Type of available power.
   e. Yield of the well.
   f. Estimated total pumping head.
   g. Host nation needs.
   h. Ease of maintenance.

   Well yield is frequently overlooked when selecting a pump for small wells. Installing a pump that handles a large discharge capacity may either temporarily drain a small well or exceed the maximum possible suction lift. Therefore, pumping requirements and well characteristics must be matched to determine the optimum pump for each installation. Figure 7-1 provides a general guide for use in pump selection. Military well drillers deploying with well-completion kits normally use the deep-well submersible pumps that are supplied with the kits.

7.2 SHALLOW-WELL PUMPS

These pumps are limited to the depth from which they lift water. At sea level, the practical limit is 22 to 25 ft for most pumps. This value decreases about 1 ft for each 1,000-ft increase in elevation above sea level. The operative principle of a shallow-well pump is similar to drinking through a straw. A partial vacuum is created, and the difference between the pressure inside the straw and the liquid outside the straw forces the liquid upward to a new equilibrium.
A pump exhausts air from the intake line, thus lowering the pressure on the intake side below atmospheric pressure. The atmospheric pressure on the water in the well then forces the water up through the suction line into the pump. The atmospheric pressure is the only force available to lift water to the pump. At sea level, the force is about 14.7 psi (about 34-ft of water). The maximum is never reached because pumps are not 100 percent efficient and because other factors (i.e., water temperature and friction or resistance to flow in the suction pipe) reduce the suction lift. Since a partial vacuum is required in the suction line, the line must be airtight if the pumps are to function properly. Threaded joints must be carefully sealed with pipe-joint compound and all connections to the pump must be tight. The list below describes various types of shallow-well pumps:

<table>
<thead>
<tr>
<th>Type of Pump</th>
<th>Practical Suction Lift</th>
<th>Usual Well-Pumping Depths</th>
<th>Usual Pressure Heads</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reciprocating:</td>
<td>1. Shallow well</td>
<td>22 to 28 -ft</td>
<td>22 to 26 -ft</td>
<td>100 to 200 -ft</td>
<td>1. Positive action</td>
<td>1. Pulsating discharge</td>
</tr>
<tr>
<td></td>
<td>2. Deep well</td>
<td>22 to 25 -ft</td>
<td>Up to 600 -ft</td>
<td>Up to 200 -ft above cylinder</td>
<td>2. Discharge against variable heads</td>
<td>2. Subject to vibration and noise</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Pumps water containing sand and silt</td>
<td>3. Maintenance cost may be high</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4. Especially adapted to low capacity and high lifts</td>
<td>4. May cause destructive pressure if operated against closed valve</td>
</tr>
<tr>
<td>Centrifugal:</td>
<td>1. Shallow well</td>
<td>20 -ft maximum</td>
<td>10 to 20 -ft</td>
<td>100 to 150 -ft</td>
<td>1. Smooth, even flow</td>
<td>1. Loses prime easily</td>
</tr>
<tr>
<td></td>
<td>a. Straight centrifugal (single stage)</td>
<td></td>
<td></td>
<td></td>
<td>2. Pumps water containing sand and silt</td>
<td>2. Efficiency depends on operating under design heads and speed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Pressure on system is even and free from shock</td>
<td>Same as straight centrifugal except maintains priming easily</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4. Low-starting torque</td>
<td>4. Abrasion from sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5. Usually reliable and good service life</td>
<td>5. Usually reliable and good service life</td>
</tr>
<tr>
<td></td>
<td>b. Regenerative vane turbine type (single impeller)</td>
<td>28 -ft maximum</td>
<td>28 -ft</td>
<td>100 to 200 -ft</td>
<td>1. Efficiency depends on operating under design head and speed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Deep well</td>
<td>Impellers submerged</td>
<td>50 to 300 -ft</td>
<td>100 to 800 -ft</td>
<td>2. Requires straight well large enough for turbine bowl and housing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>a. Vertical line shaft turbine (multistage)</td>
<td></td>
<td></td>
<td></td>
<td>3. Lubrication and alignment of shaft critical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>b. Submersible turbine (multistage)</td>
<td>Pump and motor submerged</td>
<td>50 to 400 -ft</td>
<td>80 to 900 -ft</td>
<td>1. Efficiency depends on operating under design head and speed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jet:</td>
<td>15 to 20 -ft below ejector</td>
<td>Up to 15 to 20 -ft below ejector</td>
<td>80 to 150 -ft</td>
<td>1. Same as shallow-well turbine</td>
<td>1. Repair to motor or pump requires pulling from well</td>
</tr>
<tr>
<td></td>
<td>1. Shallow well</td>
<td></td>
<td></td>
<td></td>
<td>2. Easy to frost proof installation</td>
<td>2. Sealing of electrical equipment from water vapor critical</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Short pump shaft to motor</td>
<td>3. Abrasion from sand</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1. Same as shallow-well turbine</td>
<td>1. Abrasion from sand</td>
</tr>
<tr>
<td></td>
<td>2. Deep well</td>
<td>15 to 20 -ft below ejector</td>
<td>25 to 120 -ft, 200 -ft maximum</td>
<td>80 to 150 -ft</td>
<td>1. Same as shallow-well jet</td>
<td>Same as shallow-well jet</td>
</tr>
<tr>
<td></td>
<td>Rotary:</td>
<td>22 -ft</td>
<td>22 -ft</td>
<td>50 to 250 -ft</td>
<td>1. Positive action</td>
<td>1. Capacity reduces as lift increases</td>
</tr>
<tr>
<td></td>
<td>1. Shallow wall (gear type)</td>
<td></td>
<td></td>
<td></td>
<td>2. Discharge constant under variable heads</td>
<td>2. Air in suction or return line stops pumping</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Efficient operation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1. Subject to rapid wear if water contains sand or silt</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Wear of gears reduces efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Abrasion from sand and silt</td>
<td>A cutless rubber stator increases life of pump; flexible drive coupling is weak point in pump; best adapted for low capacity and high heads</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4. Low-starting torque</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Deep well (helical-rotary type)</td>
<td>Usually submerged</td>
<td>50 to 500 -ft</td>
<td>100 to 500 -ft</td>
<td>1. Same as shallow-well rotary</td>
<td>Same as shallow-well rotary except no gear wear</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Only one moving pump</td>
<td></td>
</tr>
</tbody>
</table>

*Practical suction at sea level reduces lift 1-ft for each 1,000-ft above sea level*
1. **Pitcher-Spout Hand Pump.** This is a surface-mounted, reciprocating or single-acting piston pump (see Figure 7-2). It pumps water up to depths of 24-ft. The pump has a hand-operated plunger that works in a cylinder designed to be set on top of the well casing. The suction pipe screws into the bottom of the cylinder. The plunger has a simple ball valve that opens on the downstroke and closes on the upstroke. Usually, a check valve at the lower end of the cylinder opens on the upstroke of the pump and closes on the downstroke. Continuous upstroke and downstroke actions result in a pulsating flow of water out of the discharge pipe. By lifting the pump handle as high as possible, the check valve (lower end of the cylinder) tilts when the plunger is forced down on top of the valve. Tilting the check valve allows the pump and suction line to drain.

   To reprime the pump after draining, pour water in the cylinder from the top of the pump. To maintain the pump, renew the plunger, check the valve leathers, and clean the suction pipe. Clean the suction pipe when it becomes clogged with sand, gravel, or other material. The pump is noisy and the handle may fly up when released during the downstroke.

   A hand pump is the preferred pump choice during HCA and/or FHA projects as it pumps efficiently from shallow wells or ponds. Because it does not use power, it is also ideal for pumping water in locations without power or in an emergency during power outages.

2. **Rotary Pump.** These pumps use a system of rotating gears (see Figure 7-3) to create suction at the inlet and force a water stream out of the discharge. The gears’ teeth move away from each other at the inlet port. This action causes a partial vacuum and the water in the suction pipe rises. In the pump, the water is carried between the gear teeth and around both sides of the pump case. At the outlet, the teeth moving together and meshing causes a positive pressure that forces the water into the discharge line.

   In a rotary gear pump, water flows continuously and steadily with very small pulsations. The pump size and shaft rotation speed determine how much water is pumped per hour. Gear pumps are generally intended for low-speed operation. The flowing water lubricates all internal parts. Therefore, the pumps should be used for pumping water that is free of sand or grit. If sand or grit does flow through the gears, the close-fitting gear teeth wear, thus reducing pump efficiency or lifting capacity.

3. **Centrifugal Pump.** These are variable displacement pumps in which water flows by the centrifugal force transmitted to the pump in designed channels of a rotating impeller (see Figure 7-4). A closed case, with a spiral-shaped channel for the water and a discharge opening, surrounds the impeller. The channel gradually widens towards the outlet opening. As water flows through the channel, speed decreases and pressure increases. The hydraulic characteristics of the pump depend on the dimensions and shape of the water passages of the impeller and the case. The centrifugal pump works as follows:
Figure 7-3. Rotary Pump

Figure 7-4. Centrifugal Pump
a. Water enters the pump at the center of the impeller and is forced out by centrifugal force (The pump and suction pipe may need to be full of water before starting the pump).

b. The expelled water forces the water in the casing out through the discharge pipe, producing a partial vacuum in the center.

c. Atmospheric pressure acts on the surface of the water in the well and forces more water up the suction pipe and into the impeller to replace the expelled water.

The list below describes additional considerations:

a. **Head.** Head is the pressure against which a pump must work the suction-lift and friction losses and the system pressure that the pump must develop. If the head is increased and the speed is unchanged, the flow rate decreases. To increase the flow rate, increase the speed or decrease the head. If the head is increased beyond the pump’s (shutoff head) capacity, water is not pumped. The impeller only churns the water inside the case; the energy expended heats the water and the pump. If such action continues, enough heat may develop to boil the water and generate steam causing the impeller to rotate in vapor rather than water. With no coolant, the bearings seize, resulting in severe pump and possible motor damage.

b. **Connections.** Several pumps may be required to meet head or flow requirements. Connect the pumps either in series or in parallel. If two centrifugal pumps are connected in series (the discharge of the first connected to the suction of the second), the discharge capacity stays the same. However, the head capacity is the sum of both pumps’ head capacities. The increased head capacity is only available as discharge head; no appreciable increase is gained in suction lift. The same effect is obtainable by using a multistage pump that contains two or more impellers within one casing.

If two centrifugal pumps are connected in parallel (both suction are connected to the intake line and both discharges connected to the discharge line), the discharge head is the same as that of the individual pumps and the discharge capacity is close to the sum of the capacities of both pumps (the increased flow rates result in extra friction losses that prevent the combined flows from being the exact sum of the two pumps).

4. **Self-Priming Pump.** This pump has a priming chamber that makes repriming unnecessary when the pump is stopped for any reason other than an intentional draining. The pump is mounted on a frame with and driven by a two-cylinder, three-horsepower military standard engine (see Figure 7-5). The unit is close-coupled. The impeller is secured to an adapter shaft that is fastened and keyed to the engine stub shaft. A self-adjusting mechanical seal prevents water from leaking between the pump and the engine. The pump is designed for optimum performance with a suction lift of 10-ft. The pump is operable at greater suction lifts, but the capacity and efficiency of the unit are reduced proportionately.

a. **Installation.** Install the pump as close to the source of water supply as possible to minimize the required suction lift. Install full-sized suction piping and keep friction losses as low as possible by using the least possible number of pipe fittings (i.e., elbows, bents, unions). To ensure that joints do not leak use pipe cement or teflon tape on all joints. If a suction hose is used, try to ensure that the hose is as airtight as possible. If removing the suction, discharge piping, or hose frequently, make the connections with unions to reduce wear on the pump housing.

b. **Priming.** To prime the pump, remove the priming plug on top of the pumping case, and pour water into the pump case to the discharge-opening level. Failure to fill the priming chamber may prevent priming. If the pump takes longer than 5 minutes to prime, a mechanical problem exists. A self-priming pump is normally primed from a 9-ft suction lift in 2 minutes or less, depending on the length and size of the suction pipe. If a valve is used in the discharge line, open it wide during priming. If the pump fails to prime, look for the following:
Figure 7-5. Self-priming Pump

(1) Plugged priming hole
(2) Air leak in suction pipe or hose
(3) Collapse of lining suction hose
(4) Plugged end of suction pipe or suction strainer
(5) Lack of water in pump housing
(6) Clogged, worn-out, or broken impeller
(7) Worn or damaged seal.

7.3 DEEP-WELL PUMPS

The list below describes various deep-well pumps:

1. **Submersible Pump.** This is a centrifugal pump closely coupled with an electric motor that operates underwater. The pump is typically multistage containing two or more impellers (depending on head requirements) housed in a bowl assembly. Because the system is designed for underwater OPS, it has a waterproof electric motor, watertight seals, electric cables, and connections. The motor is located beneath the bowl assembly with the water intake screen between the two units.
Military well-completion kits contain the submersible pump (see Figure 7-6). The pump produces 50 gpm at 600 ft and is powered by a 15 horsepower, 460-volt, 3-phase electric motor. The pump comes with 700 ft of electrical conductor cable and 660 ft of 2-inch drop hose that supports the pump and brings the water to the surface distribution system. Currently, the submersible pump is the standard in deep-well, high-production systems.

WARNING

Don’t handle live electrical wires when wet or while standing in water. Do not step on exposed electrical cables.

The submersible pump is reliable and has the following characteristics:

a. Motors, cables, and seals have very low maintenance requirements.

b. Noise levels are reduced because the motor is located in the well.

c. Motor operates at a cooler temperature because it is submerged.

d. System does not require long drive shafts and bearings, so maintenance problems and deviations in vertical well alignment are not critical factor when using this pump.

The main disadvantage with the pump is that the entire pump and motor assemblies require removal from the well if repairs or services are necessary.

Figure 7-6. Submersible Pump
2. **Turbine Pump.** The turbine (line shaft) pump is a shaft-driven, centrifugal pump. The pump is hung in a well at the lower end of a string of pipe called the column pipe. The shaft, which drives the pump, runs through the column pipe and extends from the pump to the ground surface where it is connected to a pump-head assembly. Bearings in the column pipe are used to stabilize the shaft. The turbine pump (see Figure 7-7) is a multistage pump containing several impellers or bowl assemblies. The main advantage to the turbine pump is the accessibility to the power source. The power source is either a hollow-shaft electric motor or a reciprocating engine connected by a right-angle drive and is located above ground. The main disadvantages are maintenance requirements for the shaft and bearings and the requirement that the well is vertical with no deviations for installation.

3. **Helical-Rotor Pump.** This pump is a positive-displacement-, rotary-screw-, or progressing-cavity-type pump (see Figure 7-8). The pump is designed for relatively low-capacity, high-lift wells that are 4-inches or larger in diameter. The main elements of the pump are a highly polished, stainless-steel helical rotor, a single-thread worm; and an outer rubber stator. The rotor is located in the stator. During the rotation process, the rotor forces a continuous stream of water forward along the cavities in the stator producing a uniform flow. The helical-rotor pump is designed to produce 50 gpm at 1,800 rpm against a 250-ft head.

![Figure 7-7. Turbine Pump](image-url)
4. **Jet Pump.** This pump is a combination of a surface centrifugal pump, down-hole nozzle, and venturi arrangement (see Figure 7-9). It is used in small diameter wells that require a lift of 100-ft or less. The pump supplies water under pressure to the nozzle. The increase in velocity at the nozzle results in a decrease in pressure at that point, which in turn draws water through the foot valve into the intake pipe. The combined flow then enters the venturi where the velocity is gradually decreased and the pressure head is recovered. The excess flow is discharged at the surface through a control valve, which also maintains the required recirculating flow to the nozzle.

A jet pump’s efficiency is low compared to an ordinary centrifugal pump. However, other features make the jet pump a desirable pump. They are:

a. Adaptability to wells as small as 2-inches in diameter

b. Easy accessibility to all moving parts at the ground surface

c. Simple design resulting in low purchase and maintenance costs.
7.4 AIR-LIFT PUMPS

The list below describes air-lift pump considerations:

1. Principle. Water is readily pumped from a well using an air-lift pump. There are no air-lift pumps in the military supply system; however, in the field, improvisation of a pump using compressed air and the proper piping arrangement is possible. The assembly consists of a vertical discharge (eductor) pipe and a smaller air pipe. Both pipes are submerged in the well below the pumping level for about two-thirds of the pump’s length. The compressed air goes through the air pipe to within a few ft of the bottom of the eductor pipe and is then released inside the eductor pipe. A mixture of air bubbles and water forms inside the eductor pipe. This mixture flows up and out the top of the eductor pipe. The pumping action that causes water to rise as long as compressed air is supplied is the difference in hydrostatic pressure inside and outside the pipe resulting from the lowered specific gravity of the mixed column of water and air bubbles. The energy operating the air lift is contained in the compressed air and released in the form of bubbles in the water. Figure 7-10 shows the operating air-lift principle.

![Figure 7-9. Jet Pump](image)

**WARNING**

Air and fluids under pressure may cause injury. Make sure all air couplings are tight and that lines and hoses are in good condition.
Arrange an air lift with the air pipe inside the eductor pipe for both test pumping wells and well development (see Figure 7-11). The well casing is useable as the eductor pipe. However, to pump sand and mud from the bottom of a well during well development and completion, use a separate eductor pipe. This type of pump is also useful in wells that, because of faulty design, produce sand with the water. This condition quickly creates excessive wear on most pumps. By setting the educator pipe to the bottom of the screen, sand is removed before it fills the screen.

2. Installation Design.

a. Submergence. Submergence is the proportion (percentage) of the length of the air pipe that is submerged below the pumping level. Use the following formula and Figure 7-12 below to determine submergence percentage:

![Air-Lift Principle](image)

Figure 7-10. Air-Lift Principle
Figure 7-11. Air Pipe in an Eductor Pipe

\[ \% \text{submergence} = \frac{x}{y} \times 100 \]

where:

\[ x = \text{vertical distance from A to C.} \]

\[ y = \text{vertical distance from C to D.} \]

a. **Air Pressure.** To calculate the required air pressure to start the air lift, the length of air pipe submerged below the static level must be known. The area from point B to point D is the starting air pressure (see Figure 7-12). Divide the area from point C to D (Figure 7-12) by 2.31 (constant/conversion factor) to get the required air pressure (psi).

b. **Compressors.** The 350-cfm compressor on military drilling rigs is sufficient for operating an air lift. With a submergence of 60 percent, a lift not exceeding 50-ft and the compressor delivering 350-cfm of air, a well is able to pump at over 200 gpm. If more air is needed, use another compressor in parallel. The maximum pressure that the compressor produces is 200 psi, which is enough to start an airlift with about 420-ft of air pipe submerged.

![CAUTION]

Operate compressors upwind of the drilling rig. Otherwise, dust could damage the equipment.
d. Correct Air Amounts. For efficiency, the compressor must deliver the correct amount of air. Too much air causes excessive friction in the pipe lines and waste of air from incomplete expansion in the discharge pipe. Too little air results in a reduced yield and a surging, intermittent discharge. To calculate air-compressor requirements (see Figure 7-13).

e. Performance and Efficiency. The performance and efficiency of an air lift vary greatly with the percent of submergence and the amount of lift. Generally, a submergence of 60 percent or more is desirable. If a well has a considerable pumping-level depth, use a lesser submergence percent. However, if the submergence is too low, the air lift does not operate. See Figure 7-14 for performance data for air-lift pumps corresponding to different submergence conditions and lifts. The values are for properly proportioned air and eductor pipes with minimum frictional losses. The efficiencies indicated in terms of gallons of water per cubic ft of air probably cannot be fully attained in military field OPS.
<table>
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<th>Total Depth (ft)</th>
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<td>400 to 500</td>
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Figure 7-13. Pump Readings

f. Foot Piece. For best efficiency, the end of the air pipe requires a ft piece (see Figure 7-11). This device breaks the air into small streams so that the bubbles formed are as small as possible. Make a ft piece by drilling numerous small holes in a short section of pipe.

g. Discharge Pipe. Figure 7-14 illustrates an approximated discharge-pipe length. Lower submergence than those shown result in a lower pumping efficiency. The planned pumping rate must not cause an excessive drop in the water level as it reduces the submergence. The two chief losses in the discharge pipe are air slipping through the water and the water friction in the discharge line. As the velocity of discharge increases, slippage decreases and friction increases. Eductor intake loss occurs at the lower end of the pipe due to friction and to the energy required to accelerate the flow of water into the pipe.
<table>
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<th>Lift (ft)</th>
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<th>Lift (percent)</th>
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<th>Submergence (ft)</th>
<th>Starting Air Pressure (psi)</th>
<th>Gallons of Water (per cubic ft of air)</th>
<th>Cubic Feet of Air (per gallon of water)</th>
<th>Total Length of Air Line (ft)</th>
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</table>

Figure 7-14. Submergence for Air-Lift Pumping
CHAPTER 8

Well-Performance Testing Procedures

8.1 TESTING PUMPS

The permanent pump is normally used for pump testing. If using a temporary unit, it must be adequate to draw down the water and hold it at a prescribed flow rate for a period of hours. This test determines the specific capacity of the well. Estimate the yield of a small well by bailing water from the well rapidly if no pump is available. To estimate the gpm of the well, the bailer’s volume must be known and the number of times per minute the bailer is brought up full is counted. Accurately measuring drawdown is not possible during the test because the water level constantly fluctuates. The list below details additional information on testing wells:

1. **Permanent Wells.** When possible, use two different testing procedures if a pump is available, depending on the intended use of the well and the available testing time. If the well is permanently installed, a detailed test is required. Measure the static water level in the well before testing and measure the drawdown during the test. Conduct the test as follows:

   a. **Pump at a rate that lowers the water in the well about one-third of the maximum drawdown possible** (one-third the distance from the static water level to the top of the well screen) or about one-third of the rated capacity of the pump.

   b. **Monitor and adjust the flow rate early in the test because as the drawdown increases the flow rate decreases.**

   c. **Continue pumping at a constant flow rate until the drawdown remains constant (about 1 to 4 hours).**

   d. **Record the flow rate, drawdown, and testing time. Initially, take readings rapidly and then spread out the readings as the test continues. A reading schedule that doubles the time between readings is preferable. The recommended schedule is as follows: 0 (at the start of the test) 30 seconds, 1 minute, 2 minutes, 4 minutes, 8 minutes, 15 minutes, 30 minutes, 1 hour, 2 hours, 4 hours, and so forth.**

   e. **Establish the desired, constant flow rate quickly. Record the exact time of each reading (not the intended or scheduled time). After the drawdown stabilizes (1 to 4 hours), the pumping rate increases to a new, constant flow rate, which produces two-thirds of the capacity of the pump. Do not stop the pump between these test segments.**

   f. **Repeat the measurements, noting the exact time that the new flow rate is started. Try to follow the above reading schedule, starting from the time the flow rate is increased. When the drawdown stabilizes, increase the pumping rate to produce the maximum drawdown or about 90 percent of the maximum capacity of the pump. Conduct another reading schedule until the pumping level stabilizes.**

The above procedure may require modification depending on well requirements and local site conditions. However, the precision and accuracy of the measurements taken shall not change. Test results shall become a part of the permanent records. The results are useful for evaluating the efficiency of the well in the future and for determining the need for well rehabilitation. Calculating the gpm per ft of drawdown gives the capacity of the well. This information is used to estimate production and to regulate the pump’s flow rate to prevent dewatering of the well and possible pump damage.
2. **Temporary Wells.** Conduct a single-stage test rather than the step drawdown test. To establish the flow rate, conduct a 1- to 2-minute test to determine the gpm per ft of drawdown. Let the well return to the original static water level before testing (about 1 hour). Select a flow rate that produces about two-thirds of the available drawdown, but does not reach more than 90 percent of the pump’s capacity. Conduct the test as described above, but with only one segment. When the drawdown stabilizes for the selected flow rate, stop the test.

3. **Methods.** Refer to Chapter 7 for a description of pumps used in testing and well production.

   a. **Submersible-Pump Method.** Use the submersible pump in well-completion kits to pump test the water well. Set the pump deep enough to attain the maximum pumping rate and drawdown. When testing a well with a screen, set the suction of the pump above the top of the screen to prevent lowering the water level below the screen. When testing a well without a screen, try not to dewater the production part of the aquifer. For proper testing, a reliable power source is required so that testing is not interrupted. The power must be sufficient to drive the pump at a rated speed so that full capacity is developed.

   b. **Air-Lift Method.** This method is sometimes best for military field OPS, especially if the well may produce sand that could damage or reduce the life of a submersible pump. An air-lift pump has two major problems. Air turbulence could make drawdown measuring difficult and entrained air may cause considerable error in measuring the flow rate. After constructing an air-lift pump, check the pump capacity against the expected well yield. To conduct the test, set the pump according to the readings in Figure 7-13.

   An air compressor that puts out 350 cfm at 200 psi is suitable for performing most air-lift pumping OPS. To determine the amount of air needed for pumping water, use the following equation or refer to Figure 8-1.

   \[
   Q = \frac{V(60)}{T}
   \]

   where:

   - \(V\) = free air (actual) required to raise one gallon of water, in cubic ft.
   - \(h\) = total lift, in ft.
   - \(\log\) = logarithm-c value.
   - \(H\) = operating submergence, in ft.
   - \(C\) = constant (see Figure 8-2).

   The pressure required to start pumping is equal to the depth of water over the submerged end of the air pipe. After pumping has started the water in the well draws down to a working level. The air pressure required is the total lift, in ft, from the working water level plus the friction loss in the airline. Conduct the test and try to measure flow rate and drawdown quickly. Pumping creates turbulence in the well. Use the electric-line method (Paragraph 8.2) to try and measure drawdown. Because of entrained air, use the measured-container method (Paragraph 8.3) to obtain flow-rate measurements.
8.2 MEASURING WATER LEVEL

The list below describes water level measuring methods:

1. **Electric-Line Method.** Water levels are measured accurately with a two-conductor, battery-powered indicator known as a Sounder (see Figure 8-3). Well drilling units should be equipped with a well Sounder. The Sounder is a battery and a meter connected in series. When the upper wire on the tip of the Sounder touches the water in the well, the circuit completes and the meter gives a steady reading. Measure the amount of wire in the well to determine the depth to the water level. The wire is marked at 5-ft intervals for easy measuring.

2. **Tape Method.** Use this method to measure the depth to the static level in a shallow well. Conduct this test as follows:

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<tbody>
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<td>366</td>
<td>75</td>
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<td>358</td>
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<td>348</td>
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<tr>
<td>335</td>
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<td>318</td>
<td>55</td>
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<td>296</td>
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<td>272</td>
<td>45</td>
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<tr>
<td>246</td>
<td>40</td>
</tr>
<tr>
<td>216</td>
<td>35</td>
</tr>
</tbody>
</table>

**Figure 8-2.** Constants
Step. 1. Chalk one end of a weighted steel tape with carpenter’s chalk. Lower the tape (see Figure 8-4) into the well to a depth of 1 or 2 ft past the chalk (An alternative to chalk is a soluble felt-tip marker).

Step. 2. Measure the wetted length of the tape and subtract the amount from the total length lowered below the reference point to obtain the water depth. This test is accurate to within 0.01 ft.

8.3 MEASURING DISCHARGE RATE

The list below describes discharge rate measuring methods:

1. **Measured-Container Method.** The flow rate from a well or pump is determined by measuring the time required to fill a container with a known volume. With this method, use small containers for early measurements and large containers for later measurements. Also, use an instrument, such as a stop watch, for accurate time measurements. Use the following equation:
where:

\[ Q = \text{flow rate, in gpm.} \]
\[ v = \text{volume, in gallons.} \]
\[ T = \text{time required to fill container, in seconds.} \]

2. **Flow-Meter Method.** A turbine-type flow meter gives an acceptable flow-rate reading. These meters are used by civilians. A totalizer-type water meter is also acceptable when the yield is low. Use these meters to measure the total gallons pumped and determine the flow rate. To do this, record the number of gallons that flow within a set amount of time and compute the flow rate.

3. **Open-Pipe Method.** With this method, the pipe is fully open and the distance the water stream travels parallel to the pipe at a 12-inch vertical drop is measured (see Figure 8-5). Use the following procedure:

- Step 1. Measure the ID of the pipe and the distance the stream travels parallel to the pipe at a 12-inch vertical drop. The results are in inches.

- Step 2. Estimate the flow from the pipe diameter and the distance the stream travels (see Figure 8-6). The results are in gpm.

For partially filled pipes, measure either the water depth or the freeboard. Divide the diameter by the water depth to get a percentage ratio. Measure the stream as above and calculate the discharge. The actual discharge is, approximately, the value for a full pipe of the same diameter multiplied by the correction factor from (see Figure 8-7).

![Figure 8-5. Open-Pipe Flow Measurement Method](image-url)
### Horizontal Distance (inches)

<table>
<thead>
<tr>
<th>Pipe Diameter (inches)</th>
<th>12</th>
<th>14</th>
<th>16</th>
<th>18</th>
<th>20</th>
<th>22</th>
<th>24</th>
<th>26</th>
<th>28</th>
<th>30</th>
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<td>310</td>
<td>336</td>
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<td>387</td>
</tr>
<tr>
<td>6</td>
<td>352</td>
<td>410</td>
<td>470</td>
<td>528</td>
<td>587</td>
<td>645</td>
<td>705</td>
<td>762</td>
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<tr>
<td>8</td>
<td>610</td>
<td>712</td>
<td>813</td>
<td>915</td>
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<td>1,119</td>
<td>1,221</td>
<td>1,322</td>
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<td>10</td>
<td>960</td>
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<td>1,280</td>
<td>1,440</td>
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<td>1,760</td>
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<td>1,835</td>
<td>2,032</td>
<td>2,286</td>
<td>2,521</td>
<td>2,760</td>
<td>2,980</td>
<td>3,210</td>
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</tr>
</tbody>
</table>

**Figure 8-6.** Open-Pipe Flow Measurements

### Percent Factor

<table>
<thead>
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<th>Factor</th>
<th>Percent</th>
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</tr>
<tr>
<td>50</td>
<td>0.500</td>
<td>100</td>
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</tr>
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</table>

**Figure 8-7.** Correction Factors
CHAPTER 9

Cold Weather Well Construction

9.1 CONSIDERATIONS

The list below describes cold weather considerations:

1. **Cold Weather Water Supply:** Supplying water for OPS or bases in cold regions requires careful planning due to the harsh climate and ground conditions. Potable water is widespread at the surface in some cold regions, but is uncommon in more arid cold regions. Locally, surface water may be melted from ice or pumped from unfrozen lakes or glacial-melt pools. Many surface sources are only dependable during the summer months, leaving potential problems in supplying water throughout the year. More dependable, year-round supplies of groundwater may be developed through wells in relatively shallow, unfrozen strata (see Figure 9-1) and from wells that fully penetrate the permafrost.

Do not touch cold metal with your bare hands.

Permanently frozen rock and soil are widespread in seasonally or permanently frozen areas. This condition restricts groundwater development because some of the groundwater is permanently frozen and not available. The frozen zones, which vary in thickness from a few ft to 2,000 ft, are impermeable aquicludes and inhibit the upward movement of unfrozen groundwater. The difficulty of obtaining water increases northward as the permafrost thickens and becomes colder and more continuous.

![Figure 9-1. Unfrozen Strata](image)
2. **Discontinuous Permafrost.** In this zone, permafrost is thin and may be absent on the south slopes of hills, in valley bottoms containing permeable alluvial material (sand and gravel), and under surfaces that are cleared of vegetation (e.g., airport runways, farmlands, forest fire scars, and logging tracts). Obtain information from local sources regarding springs (icings), existing wells, unfrozen zones, and caves used for storage. Consider obtaining water from surface sources before drilling and developing wells in the permafrost zone. The existence of a good, year-round water source at the surface in the discontinuous zone indicates that the ground is not frozen beneath the well. Year-round springs, large streams, and lakes serve as water sources. Even if the water is nonpotable, these sources indicate windows in the permafrost where dug, driven, jetted, or drilled wells may be located.

Vegetation may indicate the presence and thickness of permafrost. Although tree roots rarely exceed a depth of 3-ft, the presence of large trees indicates that only the top of the permafrost during the thawing season is deeper than usual. Large trees along a river suggest that either the top of the permafrost is depressed to afford a limited supply of water or that permafrost may be absent. The presence of pine or aspen indicates a similar depression of the permafrost table or possibly the complete absence of permafrost. The presence of willow shrubs (not trees), peat and moss, or stunted tamarack and birches indicates a thin zone of summer thawing (active zone) and the presence of cold, thick permafrost near the surface. These indicators are more frequent in a thick, continuous permafrost zone.

3. **Thick, Continuous Permafrost.** Generally, surface sources are required when underlain by thick, continuous permafrost. Available groundwater requires drilling deep (several hundred ft) wells through the permafrost. Such a task may be beyond the scope of military OPS.

### 9.2 WELL DRILLING

The list below describes well drilling considerations in cold weather:

1. **Drilling Equipment.** The same drilling equipment for normal well drilling is required, but additional accessories are necessary because of adverse weather conditions. Portable gasoline or diesel heaters are a must for personnel and equipment at the construction site. Electrical or oil immersion heaters may also be necessary for storage and settling reservoirs. Lastly, tents or sheds are required to protect personnel from cold winds or storms.

2. **Rotary Drilling.** In permafrost regions, use the rotary-drilling method for deep drilling and large diameter holes and for shallow drilling and small holes. The procedure for rotary drilling in frigid climates is the same as in temperate climates except for temperature requirements of the drilling fluid. In adverse weather conditions (extremely low temperatures and snowstorms), construct shelters to protect the rigs and to maintain comfortable working temperatures.

   At temperatures below -20 °F, generally no drilling is done. The mud used in rotary drilling should be at near-freezing temperatures when entering the drill stem to prevent thawing and caving of the hole. When necessary, apply enough heat to the mud to prevent the hole from freezing. This may be accomplished at the mud pump with a low heat propane torch or electric heater. Make sure the rig operates continuously to prevent the mud pump and accessories, bits, and casing from freezing during OPS. If OPS must stop at night, remove the tools, let ice form over the well, and drill out the ice in the morning. In a finished well, use the rotary rig to circulate the water to prevent freezing until the pump is installed.

3. **Jet-Drive Drilling.** This is another method of constructing small wells in cold climates, in addition to either a warm or discontinuous permafrost condition. The wells are usually 2 inches in diameter and are drilled to a depth of 200 ft.

   The equipment is simple, light, and consists of a small derrick and a small engine with a cathead. The pipe is pushed into the ground and advanced manually, dropping a small weight fastened to a line running over a sheave on the derrick to the cathead. The jet point is made from a reducer, which is ground into a bullet
shape and attached to the end of the 2-inch pipe. Drill several 1/4-inch holes above the jet point a distance of 1 to 2 ft. A thaw-line pipe projects a maximum of 2 ft through the head of the drive point.

Pump a water jet through the thaw-line pipe during drilling OPS. Suspend the pipe on a simple chain hoist and slowly move the pipe up and down. The thaw-line pipe penetrates the sediments ahead of the jet point. When the thaw-line pipe is about 2 ft ahead of the jet point, retract the pipe. The casing is driven as far as possible; repeat the process. Use water no warmer than 40 °F in this process. Jet-drive drilling proceeds about three times as fast in permafrost as in thawed ground. Figure 9-2 illustrates a percussion-type drilling rig used in coldweather well drilling, and Figure 9-3 shows a jet-drive point used with the rig.

Figure 9-2. Percussion-Type Drilling Rig
For depths of 100 ft or less, one man operating a rig jet drives about 28 ft per day in frozen ground. If the ground is thawing, the footage per day is reduced. A 2-inch well equipped with a suction pump with less than 20-ft drawdown yields up to 40 gallons of water per minute. At a depth of more than 100 ft, jet-drive drilling becomes rather slow and difficult. Therefore, limit jet-drive drilling to the southern portions of the permafrost zone where possible.

4. Drilling Fluids. The fluid used in drilling through permafrost must remain in a liquid state (do not heat) during drilling OPS and must not contaminate possible water sources; although contamination is eliminated by pumping. When using mud, try to keep it from freezing by adding chemical agents such as aquigel, gel-flake, barite, fibratex, smentex, micatex, and impermex. An increase in the viscosity of the drilling mud results in a decrease in mud flow, eventually causing freezing or sticking of the bit. Be careful during periods of excessive permafrost thawing as the hole could slough during drilling.

Brine, as a drilling fluid, is not ideal in permafrost areas because it promotes contamination and excessive thawing; requiring clean drilling equipment at all times once used. It could corrode the drill string, rig, and pump and cause a skin rash on personnel. Use brine sparingly, but only when required. The well is developed by pumping after drilling, which clears the well of brine. A suitable brine solution is 35 lb of
rock salt mixed with 53 gallons of water. In the cold weather, 100 lb of rock salt is ample for drilling a 15- to 20-ft hole. Figure 9-4 shows the specific gravity of drilling fluids when using salt additives in mud-drilling OPS.

![Image](image_url)

**CAUTION**

Adding salts to drilling fluids reduces the viscosity.

5. *Air Rotary Drilling*. This is the preferred drilling method for intermediate- or large-depth wells if the appropriate equipment is available since the precautions for rotary drilling are not necessary.

6. *Well Installation and Completion*. Some of the same installation and development methods used in warm climates are also applicable in cold climates, with some precautions. Try to minimize prolonged contact of surface water with any permafrost. Doing so avoids freezing in the hole or thawing and sloughing the previously frozen wall; which may require the need to redrill. The single-string method is appropriate to install the screen and casing together for wells in rock-like permafrost because disturbance is minimal.

The potential for water freezing after the well starts routine production requires continuous review. Insulating the well by centering a regular well casing in an oversized drill hole and by packing the annulus with dry sand through the permafrost interval may suffice; accommodating continuous rather than intermittent pumping.

![Figure 9-4. Specific Gravity of Drilling Fluids](figure_url)
APPENDIX A

Army Water Supply and Well Drilling

A.1 CONCEPT

In the Army, supply of water (potable and nonpotable) in theaters of operations is the mission of Army logisticians supported by Army engineer (GE/construction) efforts. Water detection and well drilling are specialized mission sets of Army engineers.

A.2 ORGANIZATION AND SCOPE

1. **Capabilities.** Army well drilling teams are required to develop and provide adequate water resources for deployed forces and have the capabilities as described in Paragraph 1.4.

2. **Requirements.** The hazards and risks associated with water-well drilling require the highest standards of training, proficiency, and safety. The required documents listed under Army Publications in References imply specific responsibilities that apply to Army water-well teams and OPS. Accordingly, each team shall maintain, at a minimum, copies of the applicable documents and publications.

3. **Team Composition.** Army well drilling teams are typically a theater engineer command asset and should be deployed and employed by an engineer battalion (or company) capable of providing engineer expertise and needed logistical support. Since the team has limited personnel, the engineer headquarters must also plan for security at any work site. The Army well drilling team is inherently modular and deploys to the OA with the organic equipment they use to drill and complete a well. Although teams may require augmentation for force protection or other concerns, they are usually broken down into five special positions and duties, which are described in Paragraph 3.1. (See Figure A-1 for the Army modular well drilling headquarters, and Figure A-2 for the Army well drilling team capabilities.)
## WELL DRILLING HEADQUARTERS
### 05520LD00

<table>
<thead>
<tr>
<th>MISSI0N</th>
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<tbody>
<tr>
<td>To provide command and control for water resource development and well drilling.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>CAPABILITIES</th>
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<tbody>
<tr>
<td>• Provides command and control for up to 5 Well Drilling Teams, TOE 05520LD00.</td>
</tr>
<tr>
<td>• Conducts well drilling training and operations.</td>
</tr>
<tr>
<td>• Assist teams in requisitioning unique repair parts for well drilling rigs.</td>
</tr>
<tr>
<td>• Assists in obtaining materials and unique supplies required in well drilling operations.</td>
</tr>
<tr>
<td>• Assist teams in coordinating construction support for site preparation.</td>
</tr>
<tr>
<td>• Assist teams in coordinating for the hand off to quartermaster water units.</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>DEPENDENCIES</th>
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</thead>
<tbody>
<tr>
<td>Dependent on gaining unit for religious, legal, health service support, finance, personnel and administrative services, supply and field feeding support, and unit level and direct support maintenance on organic equipment.</td>
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<table>
<thead>
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<tbody>
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<td>• Force tailored with a corps, division, brigade, or battalion headquarters element.</td>
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<table>
<thead>
<tr>
<th>RULE OF ALLOCATION</th>
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</thead>
<tbody>
<tr>
<td>167 per Well Drilling Team.</td>
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</table>

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Figure A-1. Well Drilling Headquarters (05520LD00)
A.3 EQUIPMENT

Army drilling rigs are truck mounted. Current Army well drilling and well-completion equipment consists of:

1. A truck-mounted drilling machine mounted on a Navistar™ 6-by-6 truck chassis.
2. A truck-mounted tender vehicle.
3. A lightweight well-completion kit (including accessories, supplies, and tools needed for drilling a well).

Note

Consumable products used in completing the well are not organic to the organization.

The 600-ft Army WDS (see Figure A-3) is deployed with minimal preparation and support equipment anywhere in the world. With the completion kit, drillers are able to complete a well to a depth of 600 ft using mud, air, or a down-hole hammer with or without foam injection. With augmentation of an auxiliary 250 cfm air compressor, drill pipe, and 900 ft of drilling stem, the 600-ft WDS drills up to depths of 1,500 ft with additional air.
compressor set up in a variety of soil conditions using mud or drilling foam. Additional equipment includes casing elevators and slips, larger drill bits, and an additional drill stem. Well drilling teams should ensure that they have the rig accessory kit for the LP-12 to be fully mission capable. The 600-ft WDS is:

1. Air transportable by C-130 and C-5. The vehicle is equipped for tie-down as well as lift operations during transport.
2. Equipped for air-percussion drilling and for rotary drilling with mud or air.
3. Equipped to drill wells up to 600 ft.
4. Adaptable for drilling to depth of 1,500 ft.
5. Truck mounted for mobility.
6. A three-mode, water-transfer pumping system.

Note

The 600 ft WDS replaced the CF-15-S model trailer-mounted 1,500 ft well drilling machine and 1,500 ft completion kit.

A.4 FIELD WATER SUPPLY

Tactical and logistical planners determine and coordinate water support functions in the OA for the Army. Water distribution units are responsible for distribution. Preventive medicine personnel analyze, test, and certify water supplies. Together, they ensure that there is enough quality water production and distribution to continuously support the forces. Army logistics planners, using FM 10-52, Water Supplies in Theaters of Operations, estimate the required quantity and quality based on the mission, size of the supported force, dispersion of forces in the AO, and availability of various sources of water supply.

<table>
<thead>
<tr>
<th>Model: LP-12</th>
<th>Manufacturer: George E. Failing Company™</th>
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<tbody>
<tr>
<td>Shipping weight: 38,000 pounds</td>
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<tr>
<td>Fuel tank capacity: 200 gallons</td>
<td>Width: 8 feet</td>
</tr>
<tr>
<td>Hydraulic reservoir: 79 gallons</td>
<td>Height (mast lowered): 8-ft</td>
</tr>
<tr>
<td>Water injection tank: 25 gallons</td>
<td>Height (mast raised): 38-ft</td>
</tr>
</tbody>
</table>

Figure A-3. 600-ft Well Drilling System and Specifications
Army logisticians use FM 10-52-1, *Water Supply Point Equipment and Operations*, to plan the actual distribution of water to units. Logistics units, typically supply companies, normally have a water distribution platoon assigned to conduct water supply operations, including establishing and operating a water supply point. To do this effectively, Army logistics units may require Army engineering support to include things such as:

1. Building combat roads and trails to establish traffic control patterns at the distribution site.
2. Constructing improvised dams for impounding small streams to obtain a steady source of water.
3. Constructing gravel pads to ensure a steady platform for operating ROWPUs.
4. Constructing a brine pit (ROWPU support).
5. Digging intake galleries along banks of streams.
6. Improving drainage at the facility to prevent muddy conditions that may cause the area to become unusable.
7. Constructing pads for water storage blivits.
8. Constructing or repairing troop bed down, protection and AT, and maintenance facilities (because water distribution points are often long-term operations).
9. Providing diving support for the emplacement of offshore water hoses and pipelines.
10. Rehabilitating damaged wells and distribution points.

Most water supply units are equipped with two 10-mile segments of the tactical water distribution system. The tactical water distribution system is used to transport potable water from wells, desalination plants, and other sources over distances less than 10 miles (per segment) to 20,000-gallon fabric storage tanks. The system is capable of transporting water forward up to 80 miles at a rate of 600 gpm across level terrain. Engineers’ support this system by providing GE support to set up the distribution point, leveling water storage pads, and assisting with the emplacement of the hose system. The need to cross hard-surfaced roads and other obstacles requires engineers to install culverts or emplace suspension kits at various locations throughout the hose system.

**A.5 REACHBACK RESOURCES**

The use of reachback or field force engineering (FFE) refers to linking well-trained and well-equipped military and civilian deployed forces with state side teams for their technical expertise. The objective is to effectively execute USACE roles, such as engineering expertise, contract construction, real estate acquisition and disposal, environmental engineering, and water detection, in the OA, and to maximize support to the joint force commander (JFC). These teams provide rapid, actionable engineering analyses across the range of military operations in support of US forces and the nation. Reachback provides support for technical engineering analyses, geographic information systems, intelligence support, training, and equipment.

Accessing reachback support is simple and only requires deployed personnel from any military Service or other US government organization (e.g., the Department of State (DOS) and the Federal Emergency Management Agency (FEMA)) to submit a request for information (RFI) via unclassified or classified websites, e-mail, video teleconference, or by telephone to the Engineering Infrastructure and Intelligence Reachback Center (EI2RC) in Mobile, Alabama, or the TeleEngineering Operations Center (TEOC) in Vicksburg, Mississippi (see Figure A-4). Once a request is submitted, it is routed to trained response teams, centers of expertise, or laboratories for solutions. The personnel working the RFI provide the response to the requestor to solve the problem and the data is archived in a repository.
Additionally, there is extensive capability for attaining hydrology and geology information from the USACE Engineer Research and Development Center (ERDC). ERDC has a vast amount of prerecorded data on places around the world where previous wells were drilled successfully. This information is not classified and is easily attained at [http://www.sam.usace.army.mil/en/en.htm](http://www.sam.usace.army.mil/en/en.htm). Once on the site, simply click on the Water Resource Assessments link on the bottom right hand side of the page. Another method for obtaining necessary data is through exercising the established reachback processes.

<table>
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| [https://ei2rc.usace.army.mil](https://ei2rc.usace.army.mil)  
[https://teleengineering.usace.army.mil](https://teleengineering.usace.army.mil) | CEEI2RC  
TEOC  
TEOC-VTC | CESAM-EN (EI2RC)  
109 Saint Joseph Street  
Mobile, AL 36602 | COMM  
251-690-2039 |
| [http://tec.army.mil](http://tec.army.mil) | HYDRO | CEERDC, TEOC  
RM 42, BLDG 3294  
3909 Halls Ferry Rd  
Vicksburg, MS 39180-6199 | COMM  
601-634-2735 |
[http://www.teleengineering.army.smil.mil](http://www.teleengineering.army.smil.mil) | OrgMBoxCEEI2RC@usace  
TEOC@TeleEngineering  
HYDRO@TEC | Director  
Topographic Engineering Center  
Attn: CEERD-TO-H  
7701 Telegraph Rd  
Alexandria, VA 22315 | 601-634-4231 (STU-III) |

Use '@usace.army.mil' at the end of each email.

Use '.army.smil.mil' at the end of each email.

Figure A-4. Army Reachback Contact Information
APPENDIX B

Navy Well Drilling

B.1 CONCEPT

Naval mobile construction battalions (NMCBs), also known as Seabees, under the FIRST Naval Construction Division (NCD) and Navy Expeditionary Combat Command (NECC) respectively are tasked as part of their primary mission to provide water-well drilling support for the Navy and Marine Corps, other Services, and joint task forces as tasked by the unified combatant commanders (CCDRs) through the Navy component commander or an assigned joint force land/maritime component commander. To accomplish well drilling missions, task-tailored well drilling teams deploy from an NMCB by land, air, or sea.

Refer to Navy warfare publication (NWP) 4-04, Naval Civil Engineering Operations and Navy tactics, techniques, and procedures ((Navy tactics, techniques, and procedures (NTTP) 4-04.1M/Marine Corps warfighting publication (MCWP)) 4-11.5, Seabee Operations in the MAGTF for doctrinal evidence and additional information on naval construction force (NCF) capabilities.

B.2 ORGANIZATION AND SCOPE

The list below describes the Navy’s well drilling organization and scope:

1. **Capabilities.** Navy well drilling teams are required to develop and provide adequate water resources for deployed forces and have the capabilities as described in Paragraph 1.4.

2. **Requirements.** The hazards and risks associated with water-well drilling require the highest standards of training, proficiency, and safety. The required documents listed under Navy Publications in References imply specific responsibilities that apply to Navy water-well teams and OPS. Accordingly, each team shall maintain, at a minimum, copies of the applicable documents and publications.

3. **Team Composition.** A water-well drilling team is composed of a minimum number of personnel to accomplish the tasked mission. Each NMCB table of allowance (TOA) includes four water-well drilling technicians (Navy enlisted classification (NEC) 5707) and the necessary well-drilling equipment and materials to develop water wells from deep subsurface aquifers. A well drilling team is composed of qualified individuals of any Seabee rating (e.g., utilitiesman, equipment operator, construction mechanic, etc.) in grades E1 through E9; with the four NEC designated personnel forming the nucleus of the team. A chief or senior chief (E8 or E9) is usually responsible for the overall well drilling team and OPS. Although teams may require augmentation for force protection or other concerns, they are usually broken down into five special positions and duties, which are described in Paragraph 3.1.

B.3 EQUIPMENT

The list below describes the Navy’s well drilling equipment:

1. **The T2W.** The Atlas Corporation T2W model water-well drilling machine (see Figure B-1) is an all-wheel-drive, self-propelled rig. The T2W is shippable on a C-17 or larger aircraft without disassembly. The machine is an all-hydraulic, top-head drive unit with a stationary mast capable of employing standard 20-foot drill steel. The T2W has a top speed of 65 miles per hour (mph) and is designed for over-the-road mobility. It is heavy duty, highly mobile, and suitable for rapid deployment with expeditionary engineer units. Figure B-2 illustrates specifications for the T2W.
The T2W is capable of mud and air rotary drilling, rotary percussion, or down-hole hammer drilling, using an auxiliary air compressor. A mud pump, water-injection pump, in-line oiler, four corner-mounted leveling jacks, fore and aft pintle hooks, utility hoist, driller’s station, and driver’s station are part of the T2W. The T2W is deployed with a kit that includes lightweight drill steel, drill collars, tricone bits, down-hole air hammer, and miscellaneous subs and adaptors for drilling to a depth of up to 1,500 ft. Because of the various drilling capabilities, the T2W drills in any geological formation. If drilling requires the air compressor, it is brought to the site with the drill rig or delivered by a separate support vehicle. For mud-drilling OPS, teams need a water truck and the equipment to dig the mud pits. Refer to NWP 4-04, Naval Civil Engineering Operations, for a comprehensive list of NCF capabilities and equipment.

2. **Air Compressor**. One wheel-mounted, diesel-engine-driven, 750-cfm, 300-psig air compressor is included in each NMCB TOA for performing down-hole hammer drilling techniques. The WDS tender truck is capable of towing this air compressor. The T2W does not have an on-board air compressor.

3. **Well-Completion Kit**. Each NMCB water-well drilling team is responsible for coordinating or obtaining well-completion materials necessary to develop and complete assigned well(s) in advance of the team’s arrival on site. Procurement of materials for tasked projects is coordinated with the supported unit’s logistics officer and funding is always the responsibility of the supported unit. The supported unit’s logistics officer is also responsible for the resupply of necessary supplies.

Figure B-1. T2W Well Drilling Machine
## Specifications

<table>
<thead>
<tr>
<th>Manufacturer: Atlas Copco</th>
<th>Overall Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: T2W</td>
<td>Length: 531-inches</td>
</tr>
<tr>
<td>Weight: 58,000 lb GVWR</td>
<td>Width: 102-inches</td>
</tr>
<tr>
<td>Shipping Dimensions: 3,913.1 cubic feet</td>
<td>Height (Mast Up): 495 inches</td>
</tr>
<tr>
<td>Fuel Capacity: 100 gallon</td>
<td>Height (Mast Down): 148 inches</td>
</tr>
<tr>
<td>Hydraulic Reservoir: 100 gallon</td>
<td>Engine Type: Caterpillar C-13, I-6 diesel</td>
</tr>
<tr>
<td>Top Head Rotation: Low: 0-80 rpm 12,000 ft/lb</td>
<td>Trans: Fuller FRO-15219C, 10 spd manual</td>
</tr>
<tr>
<td>Medium: 0-110 rpm 8,000 ft/lb</td>
<td></td>
</tr>
<tr>
<td>High: 0-275 rpm 3,500 ft/lb</td>
<td></td>
</tr>
<tr>
<td>Drum Capacity: Main: 12,000 lb (jib out, 1,500 lb)</td>
<td>Drilling Capacity: 24 inch, 1,500 feet</td>
</tr>
<tr>
<td>Auxiliary: 4,000 lb</td>
<td>Mud Rotary: 12.25-inch hole to 1,500 feet</td>
</tr>
<tr>
<td>Sand line: 4,000 lb</td>
<td>Downhole Hammer: 8-inch to 1,500 feet</td>
</tr>
<tr>
<td>Derrick Capacity: Pulldown: 30,000 lb</td>
<td>(with sufficient air supply)</td>
</tr>
<tr>
<td>Hold back: 30,000 lb</td>
<td>Grout Pump Capacity: 30 gpm</td>
</tr>
<tr>
<td>Mud Pump Capacity: 300 gpm</td>
<td>Self Recovery Winch: 25,000 lb pull</td>
</tr>
<tr>
<td>Water Injection Pump Capacity: 25 gpm</td>
<td>(single 3/4 in line)</td>
</tr>
</tbody>
</table>

---

Figure B-2. T2W Specifications
APPENDIX C

Air Force Well Drilling

C.1 CONCEPT

Air Force well drilling teams are organized and assigned according to Air Force Instruction (AFI) 10-209, RED HORSE Program. AFI 10-209 outlines the organizational concepts and capabilities of the Rapid Engineer Deployable Heavy Operational Repair Squadron Engineers (RED HORSE). This squadron provides the Air Force with a highly mobile, self-sufficient, rapidly deployable, civil engineer, heavy construction and repair capability. The Air Force headquarters control RED HORSE. Well drilling units are assigned as a special-skills team to an operational RED HORSE unit. The RED HORSE unit provides the logistical support necessary to complete the well drilling mission and the administrative support well drilling teams require.

C.2 ORGANIZATION AND SCOPE

The list below describes the Air Force well drilling organization and scope:

1. **Capabilities.** Air Force well drilling teams are required to develop and provide adequate water resources for deployed forces and have the capabilities as described in Paragraph 1.4.

2. **Requirements.** The hazards and risks associated with water-well drilling require the highest standards of training, proficiency, and safety. The required documents listed under Air Force Publications in References imply specific responsibilities that apply to Air Force water-well teams and OPS. Accordingly, each team shall maintain, at a minimum, copies of the applicable documents and publications.

3. **Team Composition.** A water-well drilling team is composed of a minimum of eight trained personnel (Unit Task Code (UTC) 4FPRU, Small Horizontal Construction Team), equipment (UTC 4F9HK, Water-Well Drilling Rig) and tools (UTC 4F9RU, Small Horizontal Construction Team Equipment). If 24-hour OPS are required, then additional UTCs are needed (eight-person team = one shift). Teams are composed of seven Air Force Specialty Code (AFSC) 3E2X1 (construction equipment) personnel in grades E3 through E8 and one (AFSC) 2T3XX (vehicle maintenance) person in grades E4 through E6.

   The noncommissioned OIC of the team has the responsibility for well drilling and OPS. The eight-man team is usually broken down into five special positions and duties, which are described in Paragraph 3.1. The sixth member of the Air Force team provides vehicle maintenance while the seventh and eighth members are construction equipment personnel utilized for operational team safety, routine maintenance for the entire drilling set, and mud/foam utilization as needed. The final three members of the Air Force team are trained to fill in for any of the core drilling duties.

C.3 EQUIPMENT

The equipment in the RED HORSE units is not standardized and varies in make and model. Contact the RED HORSE unit directly to obtain information on water drilling equipment.

The Air Force is in the process of standardizing its well drilling equipment by procuring the GEFCO 50K Trailer-Mounted, Topdrive, Multipurpose Drill Rig. It is a top-drive, trailer-mounted, water-well drilling system consisting of a well drilling trailer, mud cleaning system, and trailer mounted compressor. Check with the program contacts for current status (see Figure C-1).
The list below describes the GEFCO 50K well drilling equipment:

1. **Drill Mission.** 1500-ft total depth (TD) capability utilizing 4 1/2-inch OD external flush drill pipe with 3 1/2-inch connections. Borehole max diameter for TD is 12 1/4 inches. Mud rotary capability is to TD. Air rotary capability is to TD. Hydraulic power is via quick coupler for 7.5 x 10 hydraulic powered mud pump and hydraulic powered mud recycling unit with flow controls at the operator’s station. Air rotary capability is to TD via a skid mounted standard 1350/350 air compressor. Capable of deploying inside a C-17/C-5 aircraft without removal of major drilling components (i.e., mast, mud pump, compressor, tophead drive).

Mud cleaning system processes 450 gpm of fluid and is self contain and powered by its own power supply. Mud pump is stand-alone unit of the Tri-Plex Centerline hydraulic variety powered by engine off mud recycling system. System is skid mounted (of oilfield design) and transportable on flat-bed tilt trailer with winch-on capability. Mud system is in two 20-ft sections to meet transport requirements (i.e., generator or hydraulic power, pumping system on one, fluid system on the other).

2. **Tophead Drive.** Vertical rail guided design, retractable back into the mast off centerline of the hole allowing wire-line access for casing and tool handling access to the borehole. Hydrostatically powered tophead rotary with an infinitely controlled rotation speed of 0 to 120 rpm and a maximum torque of 70,000 inch-lb. The stroke of the pull down and holdback cylinder allows the head to travel 29 ft up and down the mast. Measures are in-place to identify high torque mode and low torque mode to prevent damaging drill pipe. Shifting modes is accomplished via a two-speed head and/or with a 4-speed air shift transmission to meet multiple variable speed ranges. A quick disconnect adapter to accommodate a variety of tool connections is supplied with the machine.

3. **Mast.** Lattice design with a minimum rated working capacity of 50,000 lbs and a minimum working height of 30-ft under the jib boom to top of table. The sliding table retracts hydraulically to allow the setting of 16-inch OD casing minimum (minimum 18-inch table opening). Tables are equipped with a hinged section to allow easy access to the borehole: 4 1/2, 5 3/4, 6, 8, 9 7/8, and 12 3/8 inches.

4. **Air Compressor.** A Sullair single-stage rotary screw compressor rated minimum 300 cfm and 250 psi. Hydraulically driven and equipped with necessary valves, pressure gauges, and receiver tank.

5. **Main Hoist.** 50,000 lb hoist capacity via two part line configuration hoisted by a hydraulic winch with heavy-duty crown sheaves. Winch has a line speed of 80 fpm forward and reverse direction. Equipped with 150 ft of 3/4-inch nonrotating wire rope with safety swivel hook and single sheave block for 2-part line (50,000 lb) capacity for TD tool and casing handling.

6. **Hydraulic Leveling Jacks.** Four (4) hydraulic leveling jacks, with two located up front behind truck cab and two at rear of drill. Jacks are 4.5-inches column diameter with 36-inch stroke, the extension portion is equipped with a steel boot to resists side thrust and reduce wear on cylinder bore and cylinder rod. Jacks
have integrally locked check valves with thermal reliefs, 12-inch minimum swivel pads, and 16–18-inch road clearance in the full up travel position with top of jacks extended above deck. Jack controls are located at the drillers’ station. Jack pads may be removable for clearance.

7. **Single Pipe Loader**. Single pipe loader mounted on right side of mast consisting of a holding pod with hand wheel on bottom and a guide with automatic latch on top. A hand wheel to rotate pipe to unscrew lift plug and the unit swings from side of mast to center of hole for automatic line up with top head.


10. **Lubricator (Down-Hole-Hammer)**. Seven (7) gallon reservoir capacity lubricator. Electrically controlled from operators’ station, metering valve at drillers’ station to control injection rate, and the discharged plumbed to the mast stand-pipe.

11. **Remote Air Supply**. 100 psi from the compressor or truck engine air compressor system operates air powered hand tools. Regulator, air pressure gauges are provided for both supply pressure and working pressure.

12. **Drill Trailer Chassis**. 30-ft, 8-ft wide, 11-ft high mounted on a triple axle trailer. Low profile/super single tires per wheel assembly (Goodyear G465A Radial Super Single load range L 385/65R22.5).

13. **Mud Recycling System and Mud Pump**. 500 gpm, consisting of a heavy duty oilfield type skid mounted tank with one division. The tank hosts 3 centrifugal pumps, mud mixing hopper, 3 mud guns, 1 mud cleaner and dump gates. The tank includes mud slides for shakers, handrails, lights, grating, manholes for each pit and fold down walkways. Overall length of tank is 20 ft with a holding/working capacity of 3,000 gallons. Mud Pump is a Hydraulic Duplex design is capable of minimum 450 gpm at 255 psi.

14. **Air Compressor**. Skid-mounted (oilfield design) with 1350 cfm/350 psi diesel powered air compressor, constructed in a weather/sound proof (low noise) enclosure, with a minimum 3-inch diameter discharge manifold with hammer unions, wipe-check safety cables, 2 each 30-ft x 3-inch high pressure air hose, female connectors on each end, 2 each male by male spud connectors provided to connect hoses if needed. Fuel tank has capacity to operate unit for 12 continuous hours at full capacity.

15. **Air Transportability**. The complete Water-Well Drilling System is air deployable by Air Force C-17/C-5 aircraft in a drive-on/drive-off mode. This Water-Well Drilling System (to include the Well Drill Truck, Mud Cleaning System, and all other components that make up this Well Drilling System) are loadable/unloadable without the use of approach shoring or material handling equipment (e.g., forklifts, aircraft loaders, etc.). Possibly more than one C-17 aircraft may be required to accommodate this well drilling system. Major components, such as the mud pump, hoist assembly, mast, etc., are not removed either whole or partially from the vehicles to meet dimensional or weight requirements for aircraft drive-on loading. Removal or replacement of any other parts require no longer than 2 hours for a properly trained mechanic with common hand tools or special tools provided.
INTENTIONALLY BLANK
APPENDIX D

Water Resource Detection Team

D.1 CONCEPT

Detection of groundwater sources is critical for successful well drilling OPS. Without proper analysis, the potential for finding an adequate source is less likely. In unfamiliar terrain, drilling by trial-and-error (i.e., exploratory drilling or test holes) is costly and time-consuming. It is only recommended if other water detection methods are not available or are proven to be unsuccessful. Determining the most suitable sites to drill for groundwater falls primarily on geospatial teams and the WDRT.

Geospatial teams use data from terrain and other geospatial products to recommend the best sites to conduct well drilling OPS. These teams use the results of field reconnaissance and geophysical surveys to provide recommendations. Geospatial teams are not equipped or trained for actual detection, only predictive analysis. They also have the capability of reachback to experts at the TEC to obtain data and analysis from historic records and additional subject matter experts that are able to identify areas with a high potential for developing water supply sources. Contact TEC at https://tsunami.tec.army.mil/Products/WaterResources/.

The mission of the WDRT is to assist military planners, terrain teams, and all military Service well-drilling teams in locating adequate groundwater supplies before drilling to improve military well-drilling success. Through expertise and studies they identify high-potential areas for the best possible quality of water within available drilling equipment capability; in order to meet the water production requirements of the mission. The following four areas or elements are capabilities that the WRDT provides:

1. Database. The TEC produces and maintains a worldwide DOD Water Resources Database of available water supply and hydrologic data, including groundwater resources. The WRDB is derived from classified and open-source data, maps, documents, and imagery. When specific missions and requests are received for areas where data is uncertain or inconclusive, the team researches additional sources and data unique to the area. The resulting WRDT product or report summarizes the information critical to planning a successful well, such as the hydrogeology, target depth, aquifer material, expected yield, and probable water quality. Office studies, based on research and analysis of existing data, are the most cost effective and timely WRDT approach and takes hours to days to complete.

2. Remote sensing. If databases and other supplemental information are inadequate, aerial or satellite imagery is studied and analyzed for indications of groundwater. This source is especially useful in a hardrock area, where siting wells on significant fractures and fracture intersections is the key to success. The acquisition and analysis of imagery increases the time and cost to complete an office study.

3. Supporting specialists. If office studies including imagery analysis are inadequate, one or more supporting specialists may be deployed to the site. These specialists contact HN groundwater experts, collect and evaluate in-country data associated with existing or historic wells, and conduct hydrogeologic field reconnaissance of specific areas before drilling. They may also assist with interpreting well cuttings and down-hole electric logging during drilling. Field studies take days to weeks to complete.

4. Geophysics. Should information gathered by supporting specialists be insufficient, additional local site investigations may be necessary using exploratory geophysics. Geophysicists may deploy to the site to conduct electrical resistivity, seismic refraction, or other on-site tests to better define the subsurface before drilling. Geophysical exploration and data analysis generally takes weeks to complete. Costs are significantly higher than for office-based studies and are paid by the requester.
WDRT requests may be made directed to TEC by any involved stakeholder/Service and need not be approved through a chain of command. WDRT requests are examined and high-potential areas are identified through the examination of existing databases, followed by the collection and analysis of additional sources and imagery. In those rare cases when high-potential water sites cannot be identified from source data and imagery, teams from the supporting specialists and/or geophysics elements are able to deploy for on-site investigation by request. This should take place before the arrival of Service well-drillers. If deployed to an OA, the WRDT operates as a component of the theater engineer command or senior engineer organization in theater. As with any USACE capabilities, activation of the WRDT for deployment is not automatic; it must be requested through the supporting theater engineer command or through other appropriate command channels to TEC. The supported commander provides and arranges for the WRDT’s logistics and administrative support necessary for mission accomplishment.

Note

The Army TEC provides short-course training on groundwater and hydrogeologic concepts by request to all branches of Service. Traditionally this training is provided to well drilling units prior to their deployment and training is custom-tailored to the conditions that are to be encountered in the deployment area. Focus areas include: general hydrogeology and groundwater concepts, hydrogeology and expected conditions in the deployment AO, challenges to well drilling in the AO, and reachback assistance. Please contact TEC’s Hydrologic Analysis Team for further information. POC information is available at TEC’s website: https://tsunami.tec.army.mil/Products/WaterResources.
APPENDIX E

Forms

E.1 WELL DRILLING FORMS

The list below describes the well drilling forms applicable to all Services:

1. *DD Form 2678*, Well Driller’s Log (see Figure E-1).
2. *DD Form 2679*, Piping and Casing Log (see Figure E-2).
3. *DD Form 2680*, Military Water-Well-Completion Summary Report (see Figure E-3).
## WELL DRILLER'S LOG

<table>
<thead>
<tr>
<th>DRILLER(S)</th>
<th>INITIALS</th>
<th>DATE/TIME</th>
<th>DEPTH</th>
<th>VISCOSITY</th>
<th>TYPE OF FORMATION</th>
<th>BIT SIZE/TYP</th>
<th>REMARKS</th>
<th>WATER</th>
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</thead>
<tbody>
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<td>b</td>
<td>c</td>
<td>d</td>
<td>e</td>
<td>f</td>
<td></td>
<td>(1) YES (2) NO</td>
</tr>
</tbody>
</table>

### Figure E-1: Well Drillers Log (Sheet 1 of 2)
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<thead>
<tr>
<th>DRILLER(S)</th>
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<th>DEPTH</th>
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<th>TYPE OF FORMATION</th>
<th>BIT SIZE/TYPE</th>
<th>REMARKS</th>
<th>h. WATER</th>
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<td>b.</td>
<td>c.</td>
<td>d.</td>
<td>e.</td>
<td>f.</td>
<td>g.</td>
<td>(1) YES</td>
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</table>

Figure E-1: Well Drillers Log (Sheet 2 of 2)

DD Form 2678, OCT 93 (BACK)
## PIPING AND CASING LOG

<table>
<thead>
<tr>
<th>1. WELL NUMBER</th>
<th>2. LOCATION</th>
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<td>a. COUNTRY</td>
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<td></td>
<td>b. MAP</td>
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</tbody>
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<th>3. TOWER NUMBER</th>
<th>4. OTHER</th>
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<tr>
<td></td>
<td>c. SHEET NUMBER</td>
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<table>
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<tr>
<th>5. PIPE SIZE AND USE</th>
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<tr>
<th>6. DRILLING DETAILS</th>
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<table>
<thead>
<tr>
<th>DRILLER(S)</th>
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<th>DATE/TIME</th>
<th>IN-PLACE TIME</th>
<th>LENGTH EACH PIPE</th>
<th>LENGTH CUMULATIVE</th>
<th>WEIGHT EACH PIPE</th>
<th>WEIGHT CUMULATIVE</th>
<th>WEIGHT INDICATOR</th>
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DD Form 2679, OCT 93
<table>
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<th>IN-PLACE TIME</th>
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<th>LENGTH CUMULATIVE</th>
<th>WEIGHT EACH PIPE</th>
<th>WEIGHT CUMULATIVE</th>
<th>WEIGHT INDICATOR</th>
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</tr>
</tbody>
</table>

Figure E-2. Piping and Casing Log (Sheet 2 of 2)

DD Form 2679, OCT 93 (BACK)
Figure E-3. Military Water-Well-Completion Summary Report (Sheet 1 of 2)
### Figure E-3. Military Water-Well-Completion Summary Report (Sheet 2 of 2)

#### 21. OVERBURDEN MATERIALS
- a. Unconsolidated
- b. Sandstone
- c. Limestone
- d. Igneous
- e. Other (Specify)

#### 22. AQUIFER MATERIALS
- a. Sand and Gravel
- b. Sandstone
- c. Limestone
- d. Igneous

#### 23. MARKER BEDS (Describe)
- at __________ feet
- at __________ feet
- at __________ feet
- at __________ feet

#### 24. WATER QUALITY
- a. Tested
- (1) Yes
- (2) No
- (3) Date
- b. Fresh
- c. Brackish
- d. Saline

#### 25. SKETCH OF LOCATION

#### SCALE __________

#### 26. REMARKS

#### 27a. SUBMITTED BY (Type or print name)

#### 27b. GRADE/RANK

#### 27c. UNIT

#### 29. SIGNATURE OF PROJECT OFFICIAL

#### 30. DATE OF SIGNATURE

---

*DD Form 2680, OCT 93 (BACK)*
REFERENCES

The following sources are cited or paraphrased in NTRP 4.04.2.13/FM 3-34.469/AFMAN 32-1072 (DECEMBER 2008).

ARMY PUBLICATIONS

1. FM 3-34.610 (5-33), Terrain Analysis.
2. FM 3-34.310 (5-34), Engineer Field Data.
3. FM 3-34.23 (5-116), Engineer Operations: Echelons above Corps.
4. FM 3-34.494 (5-125), Rigging Techniques.
5. FM 4-20.21 (10-52), Water Supply in Theaters of Operations.

MULTISERVICE PUBLICATIONS

7. FM 21-10/MCRP 4-11.1D, Field Hygiene and Sanitation.
8. NTTP 4-04.1/MCWP 4-11.5, Seabee Operations in the MAGTF

NAVY AND MARINE CORPS PUBLICATIONS

9. MCWP 4-11.6, Petroleum and Water Logistics Operations.
10. NWP 4-04, Naval Civil Engineering Operations

NONMILITARY PUBLICATIONS

12. Geology and Geophysics for Military Well Drillers. (Vicksburg, Mississippi: Geotechnical Laboratory, US Army Engineers Waterways Experiment Station, n.d).


Hydrologic Atlas (HA)

HA 730-A, Introduction and National Summary
HA 730-B, California, Nevada
HA 730-C, Arizona, Colorado, New Mexico, Utah
HA 730-D, Kansas, Missouri, Nebraska
HA 730-E, Oklahoma, Texas
HA 730-F, Arkansas, Louisiana, Mississippi
HA 730-G, Alabama, Florida, Georgia, South Carolina
HA 730-H, Idaho, Oregon, Washington
HA 730-I, Montana, North Dakota, South Dakota, Wyoming
HA 730-J, Iowa, Michigan, Minnesota, Wisconsin
HA 730-K, Illinois, Indiana, Kentucky, Ohio, Tennessee
HA 730-L, Delaware, Maryland, New Jersey, New York, North Carolina, Pennsylvania, Virginia, West Virginia
HA 730-N, Alaska, Hawaii, Puerto Rico, and the US Virgin Islands

STANDARDIZATION AGREEMENTS (STANAGS)


REQUIRED PUBLICATIONS

Required publications are sources that users must read in order to understand or comply with this publication.

AIR FORCE PUBLICATIONS

19. AFI 10-209 (AFR 93-9), RED HORSE Program.


22. Applicable OPS, maintenance, repair, and repair parts manuals for the assigned well-drilling rig.


ARMY PUBLICATIONS

24. FM 3-34.214 (5-250), Explosives and Demolitions.

25. FM 3-34.450 (5-410), Military Soils Engineering.

26. FM 3-34.452 (TM 5-545), Geology.


DEPARTMENT OF DEFENSE (DOD) FORMS AND PUBLICATIONS

29. DD Form 2678, Well Driller’s Log.

30. DD Form 2679, Piping and Casing Log.

31. DD Form 2680, Military Water-Well-Completion Summary Report.


MULTISERVICE PUBLICATIONS


NAVY PUBLICATIONS

34. Applicable NMCB operations orders.

35. Applicable repair parts manual.


37. NEC 5707 Water Well Drillers course data and CD.

38. Water Well Special Construction Battalion Training (SCBT) course data.

NONMILITARY PUBLICATIONS


42. NL Industries, Baroid Drilling Mud Data Book (Houston, Texas: Baroid Division, NL Industries, 1954).

RECOMMENDED READINGS

ARMY PUBLICATIONS

43. AR 614-200, Enlisted Assignments and Utilization Management.

44. AR 735-5, Policies and Procedures for Property Accountability.

45. AR 750-1, Army Materiel Maintenance Policy.
46. FM 3-34, Engineer Operations.
47. FM 3-34.400 (5-104), General Engineering.
48. FM 3-34.405 (5-412), Project Management.
49. FM 3-34.420 (5-434), Earthmoving Operations.
50. FM 3-34.433 (5-233), Construction Surveying.
51. FM 6-22 (22-100), Army Leadership.
52. FM 7-1 (25-101), Battle Focused Training.
54. TM 5-3820-256-24-1, Drilling Machine, Model LP-12 (NSN 3820-01-246-4276).
55. TM 5-3820-256-24-2, Support Vehicle, Model LP-12 (NSN 3820-01-246-4276).
56. TM 5-3820-256-24-3, Drilling System Trucks, Model LP-12 (NSN 3820-01-246-4276).
57. TM 5-3820-256-24-4, Drilling System Trucks, Model LP-12 (NSN 3820-01-246-4276).
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60. TM 5-3820-256-24P-1, Drilling Machine, Model LP-12 (NSN 3820-01-246-4276).
61. TM 5-3820-256-24P-2, Drilling Machine Truck, Model LP-12 (NSN 3820-01-246-4276).
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GLOSSARY

**air-lift method.** A pump-testing method that uses an air-lift pump.

**air rotary drilling.** A well drilling method that uses compressed air as the circulating fluid.

**alluvium.** Soils that are deposited by running water.

**annular.** Shaped like or forming a ring.

**ant-mound-like openings.** See also qanat

**aquagel.** Commercial chemical agent added to mud drilling fluid to prevent it from freezing. See also barite; fibratex; gel-flake; impermex; micatex.

**aquiclude.** Subsurface rock or soil unit, such as clay, shale, and unfractured igneous and metamorphic rock that do not transmit water readily and cannot be used as a water-supply source. Aquiclude is often used interchangeably in well drilling literature with aquitard. See also aquitard.

**aquifer.** Saturated rock or soil unit, such as gravel, sand, sandstone, limestone, and fractured igneous and metamorphic rock, that has sufficient hydraulic conductivity to supply water for a well or spring.

**aquitard.** A unit that retards or slows the passage of water. Aquitard is often used interchangeably in well drilling literature with aquiclude. See also aquiclude.

**attapulgite.** Commercially processed clay used for drilling in brackish or salty water.

**backwashing.** Pumping water into the well under pressure, forcing it out of the screened section and up the annulus.

**bail.** To make void or empty of contents. Also the mechanism that allows material in and out of the bottom of a bailer.

**bailer.** A mechanical device used to remove material from a hole.

**bail-down method.** Installing screen using a special end fitting.

**bail-down placement.** A method of simultaneously placing the gravel pack and installing the screen.

**barafos.** A white, granular sodium tripolyphosphate thinner and dispersant added to drilling fluid to prevent mud from sticking to sand grains.

**barite.** Commercial chemical agent added to mud drilling fluid to prevent it from freezing. See also aquagel; fibratex; gel-flake; impermex; micatex.

**basalt.** An igneous rock that is a very productive water bearer.
bentonite. Commercially processed clay used for drilling; bentonite forms naturally from decomposition of volcanic ash, consists of aggregates of flat platelets, and contains sodium montmorillonite, which is important in building viscosity.

boundary indicators. Characteristics indicative of local or regional groundwater flow systems.

casing ring and slip. A device used to suspend the casing at the ground surface and for pulling pipe from the hole using jacks under each side of the casing ring.

catchment. Formation whine impervious rock underlies a zone of fractured rock or alluvium that serves as a reservoir for infiltrated water; a catchment is a special type of aquifer.

cathodic protection. See also sacrificial anode.

centrifugal pump. A variable displacement pump in which water flows by the centrifugal force transmitted to the pump in designed channels of a rotating impeller.

closed-well method. A compressed-air method that involves using compressed air to close the top of the well with a cap. By arranging the equipment so air pressure builds up inside the casing water is forced out through the screen openings.

combat zone. That area required by combat forces for the conduct of operations. See also communications zone. (JP 1-02. Source N/A.)

communications zone (COMMZ). Rear part of a theater of war or theater of operations (behind but contiguous to the combat zone) which contains the lines of communications, establishments for supply and evacuation, and other agencies required for the immediate support and maintenance of the field forces. See also combat zone. (JP 1-02. Source: JP 4-0)

compressed-air methods. A rapid and effective method of transferring water during well-development by using the potential energy created by pressurized air. See also closed-well method; open-well method.

CON DET. A wetting agent added to drilling fluid to increase the dispersion action of polyphosphates.

confined aquifer. An aquifer that is completely filled with water and is overlaid by a confining bed.

confining bed. Aquiclude that exists between aquifers. Water moves only within the aquifer.

consolidated deposit. Rock that consists of mineral particles of different sizes and shapes.

continuous permafrost. A zone where permafrost is thick with no unfrozen ground. See also discontinuous permafrost; permafrost.

crop irrigation. Surface indicator that shows the use of surface water or groundwater for agriculture.

Darcy’s Law. Principle that describes the flow of groundwater.

discharge. Water that moves from one area into another.

discontinuous permafrost. A zone where permafrost is thin and maybe absent on the south slopes of hills, in valley bottoms containing permeable alluvial material, and under surfaces that have been cleared of vegetation. See also continuous permafrost; permafrost.
**dispersion treatment.** Adding dispersing agents to drilling fluid, backwashing, jetting water, or water standing in the well to counteract the tendency of mud to stick to sand grains.

**dissolution potential.** The possibility of developing high secondary permeability in a soluble rock because the rock dissolves through contact with groundwater.

**dolomite.** A carbonate rock that dissolves when carbon dioxide from the atmosphere and groundwater mix to form carbonic acid.

**double-casing placement.** A method of placing gravel using a temporary outer casing.

**drainage basin.** An area drained by a stream or river. See also hydrographic basin (local drainage basin); major river basin; regional river basin.

**drawdown.** Measure of how much the water level near the well is lowered when the well is pumped.

**draw works.** Main drill-head hoists that are mechanically or hydraulically driven wire-line winches.

**driven method.** Driven wells consist of a series of pipes with a point and a perforated pipe at the end in which the point is forced into the ground.

**drive point.** Perforated pipe with a steel point at the lower end to break through pebbles or thin, hard layers.

**dump-bailer method.** Placing grout in a casing using a dump-bailer machine.

**electric-line method.** A procedure to measure the water level using a sounder. See also sounder.

**elevator (casing).** A device used to handle pipe; the elevator is clamped around the pipe directly under the coupling. See also sand line.

**evaporite.** Sedimentary rock that is generally capable of storing and transmitting groundwater but tends to dissolve in the water

**E-Z Mud.** A synthetic, inorganic polymer. See also polymer; Poly-Sal; Revert.

**fall-in.** Material that accumulates in the bottom of the borehole after circulation stops.

**feed drive.** Mechanism on a rotary rig that applies a downward thrust to the drill string.

**fibratex.** Commercial chemical agent added to mud drilling fluid to prevent it from freezing. See also aquagel; barite; gel-flake; impermex; micatex.

**filter cake.** Solids from the drilling mud deposited on the borehole wall as the water phase is lost into the formation.

**fish.** Portion of the drill string left in the borehole. See also fishing, string failure.

**fishing.** An attempt to retrieve the portion of the drill string left in the borehole. See also fish, string failure.

**flow-meter method.** A procedure used to measure flow rate using a turbine-type flow meter.
**foamer.** Substance used in air rotary drilling to enhance the air’s ability to carry cuttings and reduce the velocity required to clean the borehole.

**foot piece.** A device at the end of an air pipe that breaks the air into small streams so that bubbles that are formed are as small as possible.

**foreign humanitarian assistance (FHA).** Programs conducted to relieve or reduce the results of natural or man-made disasters or other endemic conditions such as human pain, disease, hunger, or privation that might present a serious threat to life or that can result in great damage to or loss of property. Foreign humanitarian assistance provided by US forces is limited in scope and duration. The foreign assistance provided is designed to supplement or complement the efforts of the host nation civil authorities or agencies that may have the primary responsibility for providing foreign humanitarian assistance. Foreign humanitarian assistance operations are those conducted outside the United States, its territories, and possessions. (JP 1-02. Source: JP 3-33.)

**formation stabilizer.** Material placed on the outside of the screen to help prevent deterioration of the annular space; using formation stabilizer is an alternative method to using gravel-pack material.

**gel-flake.** Commercial chemical agent added to mud drilling fluid to prevent it from freezing. See also aquagel; barite; fibratex; impermex; micatex.

**gel strength.** Thickness of drilling mud at rest.

**geologic structure.** Feature, such as a fold, fracture, joint, or fault, that disrupts the continuity of rock units.

**geyser effect.** A result of denser mud in the annular space flowing down the hole and forcing the clean drilling mud up the drill rods.

**going crooked.** A deviated borehole.

**gravel pack.** An artificial sand filter.

**gravity-outflow method.** A backwashing method that involves pouring water into the well rapidly to produce outflow through the screen openings.

**helical-rotor pump.** A positive-displacement, rotary-screw- or progressing-cavity-type pump designed for relatively low-capacity, high-lift wells that are 4 inches or larger in diameter.

**humanitarian and civic assistance (HCA).** Assistance to the local populace provided by predominantly US forces in conjunction with military operations and exercises. This assistance is specifically authorized by Title 10, United States Code, Section 401 and funded under separate authorities. Assistance provided under these provisions is limited to (1) medical, dental, and veterinary care provided in rural areas of a country; (2) construction of rudimentary surface transportation systems; (3) well drilling and construction of basic sanitation facilities; and (4) rudimentary construction and repair of public facilities. Assistance must fulfill unit training requirements that incidentally create humanitarian benefit to the local populace. See also foreign humanitarian assistance. (JP 1-02. Source: JP 3-57.)

**hydraulic conductivity.** A measurement of the relative flow of water through a subsurface material; the results of the measurement are related to the size and spacing of particles or grains in soils or to the number and size of fractures in rocks.

**hydrographic basin (local drainage basin).** Subdivision of a regional river basin. The boundaries of hydrographic basins are usually represented by mountains or hills, which restrict the flow of water, and by low
areas where the water is discharged out of the basin. See also drainage basin; major river basin; regional river basin.

**hydraulic gradient.** Slope of the water table. Determines the direction of groundwater flow.

**hydrologic cycle.** The constant movement of water above, on, and below the earth’s surface.

**igneous rock.** Rock that forms when hot molten material (magma) cools or solidifies either inside the earth’s crust or on the earth’s surface (lava). See also lava; magma.

**impermeable barriers.** Features (solid rock masses) through which groundwater cannot flow.

**impermex.** Commercial chemical agent added to mud drilling fluid to prevent it from freezing. See also aquagel; barite; fibratex; gel-flake; micatex.

**infiltration.** The absorption of rainwater by the ground on which it falls.

**inside-tremie method.** Placing grout in the bottom of the hole through a tremie pipe that is set inside the casing.

**jet-drive drilling.** A method of constructing small wells in cold climates; the wells are usually 2-inches in diameter and are drilled to a depth of 200 feet.

**jet pump.** A combination of a surface centrifugal pump, a down-hole nozzle and a venturi arrangement used in small diameter wells requiring a lift of 100 feet or less.

**jetted well.** A well that is dug using a high velocity stream of water. See also wash-in method.

**jetting method.** A backwashing method that involves using a jetting tool to remove caked drilling mud from the borehole wall; this method requires a large water supply.

**karst topography.** Results from the dissolution of carbonate rocks by groundwater and is characterized by caves, sinkholes, closed depressions, and disappearing streams.

**lava.** Magma that cools or solidifies on the earth’s surface. See also igneous rock; magma.

**limestone.** A carbonate rock that dissolves when carbon dioxide from the atmosphere and groundwater mix to form carbonic acid.

**lithification.** The process by which sediments are converted to rock. Lithification includes compaction, consolidation, cementation, and desiccation.

**loss zone.** Area where grout is lost into the formation.

**lost circulation.** Volume loss of the drilling fluid returning to the surface.

**magma.** Hot molten rock material. See also igneous rock; lava.

**major river basin.** Largest member in the river basin grouping (e.g., the Mississippi River Basin). See also drainage basin; hydrographic basin (local drainage basin); regional river basin.
Marsh funnel. Device used to test mud viscosity; the funnel is 12-inches long and 6-inches in diameter, and it has a No 12 mesh strainer, a 1,500-ml cone, a 2-inch-long calibrated hard-rubber orifice (inside diameter of 3/16 inch), and a 1,000-ml capacity cup.

Marsh-funnel test. Procedure routinely conducted to determine the thickness or apparent viscosity of drilling fluid.

measured-container method. A procedure used to determine flow rate from a well or pump by measuring the time required to fill a container with a known volume.

metamorphic rock. Igneous, sedimentary, or preexisting metamorphic rock that preexisting metamorphic rock that undergoes further transformation by changes in pressure, temperature or chemistry.

micatex. Commercial chemical agent added to mud drilling fluid to prevent it from freezing. See also aquagel; barite; fibratex; gel-flake; impermex.

mud pump. A positive-displacement double-acting piston pump with capacities ranging from one to several hundred gallons per minute at pressures up to several hundred pounds per square inch.

mud rotary drilling. A well drilling method that uses mud to circulate the drilling fluid during the drilling process.


open-pipe method. A procedure to measure discharge rates using a fully open pipe and measuring the distance the water stream travels parallel to the pipe at a 12-inch vertical drop.

open-well method. A compressed-air method that involves establishing the surging cycle by pumping from the well with an air lift and by dropping the air pipe suddenly to cutoff the pumping action.

outside-tremie method. Placing grout outside the casing using a tremie pipe; this method is not recommended for depths greater than 100 feet.

particle slip. Downward movement of an object through fluid.

pendulum effect. Action of creating a straight borehole from a weighted drill string and bit.

perched aquifer. An aquifer that lies above an unconfined aquifer and is separated from the surrounding groundwater table by a confining layer.

percussion drilling. A method of drilling that involves crushing by impact from the teeth of the drill bit percussion drilling for water wells uses down-hole, pneumatic-percussion hammer drills.

permafrost. Permanently frozen subsoil. See also continuous permafrost; discontinuous permafrost. (JP 1-02. Source: N/A)

permeability. The capacity of a porous rock or soil to transmit a fluid.

pH (potential of hydrogen). A negative logarithm of the hydrogen-ion concentration. A value of seven is neutral. Low numbers are acid; large numbers are alkaline.

pipe clamp. A device used to hold the pipe at any position in the hole during drilling operations.

pitcher pump. A surface-mounted, reciprocating or single-acting piston pump.
playa. Dry lake bed comprised mainly of clay and located in an intermountain valley.

Pogonip. A bioclastic limestone interbedded with olive-gray shale and in the upper 100 meters from the surface usually has a few beds of reddish-brown quartzite and brownish-gray coralline dolomite.

polymer. A water-based, organic, inorganic, natural, synthetic, or synthetically-formulated additive. Polymers are formulated for various drilling fluid purposes and is used alone or to enhance clay muds. See also E-Z Mud; Poly-Sal; Revert.

Poly-Sal. Synthetic, inorganic polymer. See also polymer; E-Z Mud; Revert.

population distribution. Surface indicator that could indicate water availability because of population density.

porosity. The ratio of volume of the pore space, or voids, to the total volume of the soil or rock.

potentiometric surface. The surface that water rises to in a casing once hydrostatic pressure is released from an aquifer.

precipitation. Moisture released from clouds to the earth in the form of rain, sleet, hail, or snow.

pressure-pumping method. A backwashing method that involves capping the casing and pumping water into the well under pressure.

pull-back method. A way of installing telescoping screen.

pulldown. See also feed drive.

pump-surge method. A backwashing method that involves alternately pumping water to the surface and letting water run back into the well through the pump-column pipe.

qanat. A man-made, gently inclined underground channel that allows groundwater to flow from alluvial gravels at the base of hills to dry lowland. Qanats appear as a series of ant-mound-like openings that run in a straight line and act as air shafts for a channel. See also ant-mound-like openings.

recharge. The replenishment of an aquifer with water.

recharge area. Area where the groundwater reservoir is replenished.

regional river basin. Subdivision of a major river basin (e.g., the Missouri River Basin is a regional river basin of the Mississippi River Basin). See also drainage basin; hydrographic basin (local drainage basin); major river basin.

reservoir indicators. Characteristics in soils, rocks, and landforms that define the ability of an area to store and transmit groundwater but which do not directly indicate the presence of groundwater.

Revert. A natural, organic polymer fluid derived from the guar plant. See also polymer; E-Z Mud; Poly-Sal.

ringing off. Fatigue failure in the drill-rod joints caused by excessive torque or thrust or by borehole deviation.

riparian vegetation. Dense strands of vegetation along stream channels.

rivers. See also streams and rivers.
rock development. A well-development method used in rock formations that involves combining jetting with air-lift pumping to wash out fine cuttings, silt, and clay.

rotary pump. A pump that uses a system of rotating gears to create a suction at the inlet and force a water stream out of the discharge.

rotary table. Rotating platform on a rotary rig that transmits torque to the drill rod through the kelly.

runoff. Precipitation on land surfaces that flows along the surface into streams without infiltrating.

sacrificial anode. A simple method of protecting metal casing from corrosion by connecting a galvanically active metal bar to the casing. See also cathodic protection.

salt encrustation. Surface indicator that often occurs in playas and is indicative of saline groundwater.

saltwater encroachment. Movement of salt water into zones previously occupied by fresh water.

saltwater intrusion. Invasion of salt water into fresh water during pumping.

sanded in. A condition that exists when the string becomes stuck when cuttings collect on the bit and collar shoulder.

sand line. Device used with the elevator for lifting one or two half-lengths of pipe. See also elevator (casing).

sandstone. Consolidated or cemented sand.

saturated thickness. Distance between the top of the groundwater and the bottom of the aquifer.

sedimentary rock. Rocks that are composed of sediments that are converted to rock through compaction cementation or crystallization.

self-priming pump. A pump with a priming chamber that makes repriming unnecessary when the pump is stopped for any reason other than an intentional draining.

semipermeable barriers. Features (faults or fractured rock masses) that restrict water flow but do not act as complete barriers.

shale. Fine-grained sedimentary rock that does not store much groundwater and does not transmit large quantities of groundwater.

single-string method of installing casing. Installing casing and screen (already joined) in a single assembly. See also single-string method of installing screen.

single-string method of installing screen. See also single-string method of installing casing.

smentex. Commercial chemical agent added to mud drilling fluid to prevent it from freezing. See also aquagel; barite; fibratex; gel-flake; impermex; micatex.

snow-melt pattern. Surface indicator that provides evidence of recharge areas and directions of groundwater flow.
soil moisture. Surface indicator that provides some indication of recharge and discharge areas; soil moisture content is related to local rainfall and to grain size.

sounder. Two-conductor, battery-powered indicator used to measure water levels. See also electric-line method.

specific retention. Water that cannot be pumped out of a well.

specific yield. Water that is able to be pumped from a well.

spring. Effluence of groundwater occurring where the water table intercepts the ground surface; a spring is a good surface indicator of the presence of shallow groundwater occurrences.

spudding. Raising or lowering the drill string.

spudding in. Starting the borehole.

squeezing. In-hole effects of swelling soil (shale or clay) that absorbs water from the drilling fluid. See also swelling soil.

stabilizers. Items, such as a drill collars, used on the drill string during drilling operations.

stave tank. A collapsible and portable 1,000 gallon water container.

streams and rivers. Surface indicators that are usually recharge areas in arid regions and may be recharge or discharge areas in temperate climates; areas adjacent to streams are considered good locations for wells but are not always the best available areas for water wells because of soil content. See also rivers.

string failure. A condition that exists when the drill string parts, leaving a portion in the borehole. See also fish; fishing.

submergence. The proportion (percentage) of the length of the air pipe that is submerged below the pumping level.

submersible pump. A centrifugal pump closely coupled with an electric motor that is operated underwater.

submersible-pump method. A pump-testing method that uses a submersible pump to pump test the water well.

surface indicators. Features that suggests the presence of groundwater.

surface-water divide. Boundary between groundwater flow systems.

surge-block method. A backwashing method that involves developing a well by surging water up and down the casing with a surge block or plunger.

swelling soil. In-hole effects of shale or clay that absorb water from the drilling fluid. See also squeezing.

T. A pipe capable of receiving two hoses from either end.

tape method. Procedure to measure the depth to the static level in a shallow well.

theater. The geographical area for which a commander of a geographic combatant command has been assigned responsibility. (JP 1-02. Source: JP 1.)
thixotropic. A substance that is gel-like when still, but liquid when agitated.

top head. A mechanism on a rotary rig that moves down along the rig mast as the boring is advanced and is raised to the top of the mast to add a length of drill pipe; the top-head drive uses a power swivel.

transmissivity. The product of hydraulic conductivity and the saturated thickness expressed in gallons per day per foot of aquifer width.

transpiration. The process by which water that has traveled from the ground through the plant’s system is returned to the air through the leaf system.

tremie. A long tube or box used for depositing concrete under water, by a process of continuous filling at the upper end and discharging at the lower, accomplished by a slight churning motion.

tremie placement. Placing gravel-pack material using a tremie pipe.

tricone bit. A bit that consists of three cone-shaped rollers with steel teeth milled into the surfaces.

turbine pump. A shaft-driven, multistage, centrifugal pump containing several impellers or bowl assemblies.

uncased-interval method. Installing casing in wells located in rock formations.

unconfined aquifer. An aquifer that is partly filled with water, has fluctuating water levels, and receives direct recharge from percolating surface water.

unconsolidated deposit. Consists of weathered rock particles of varying materials and sizes.

unscreened well. A well in competent rock that does not require a screen; the aquifer is tapped through numerous, irregularly-spaced fractures.

vegetation type. Surface indicator that helps define the location of recharge and discharge areas end groundwater.

viscosity. In general, the resistance to flow or alteration of shape, by any substance as a result of molecular cohesion; most frequently applied to liquids as the resistance of a fluid to flow because of a shearing force.

wall stuck. A condition that exists when the alignment of a fine-grained soil or shale hole deviates significantly and the drill pipe wallows into the wall.

washdown method. Installing screen in an aquifer that is composed of fine to coarse sand with little or no gravel.

wash-in method. Installing casing by advancing the borehole for an expedient jetted well construction. See also jetted well.

water table well. A well drilled into an unconfined aquifer.

wetlands. Marshes, bogs, and swamps that is indicative of very shallow groundwater.

yield. Volume of water discharged from a well per unit of time when water is being pumped or is flowing freely.

yield point. Mud quality broadly included in viscosity.
# LIST OF ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
<td>Air Combat Command</td>
</tr>
<tr>
<td>AFI</td>
<td>Air Force instruction</td>
</tr>
<tr>
<td>AFMAN</td>
<td>Air Force manual</td>
</tr>
<tr>
<td>AFSC</td>
<td>United States Air Force specialty code</td>
</tr>
<tr>
<td>AR</td>
<td>Army Regulation</td>
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<tr>
<td>AWWA</td>
<td>American Water Works Association</td>
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<tr>
<td>BOM</td>
<td>bill of materials</td>
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<tr>
<td>CBRN</td>
<td>chemical, biological, radiological, and nuclear</td>
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<td>cc</td>
<td>cubic centimeter</td>
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<td>combatant commander</td>
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<td>cubic feet per minute</td>
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<td>communications zone</td>
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<td>CPM</td>
<td>critical-path method</td>
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<td>CPS</td>
<td>centimeters per second</td>
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<td>CSS</td>
<td>combat service support</td>
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<td>DA</td>
<td>Department of the Army</td>
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<td>DAPS</td>
<td>Document Automation and Production Service</td>
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<tr>
<td>DD</td>
<td>Department of Defense (form)</td>
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<tr>
<td>DOD</td>
<td>Department of Defense</td>
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<tr>
<td>DOS</td>
<td>Department of State</td>
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<tr>
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<td>Engineering Infrastructure and Intelligence Reachback Center</td>
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<td>Engineer Research and Development Center</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<td>Fahrenheit</td>
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<td>FFE</td>
<td>field force engineering</td>
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<td>ppm</td>
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