RECLAMATION
Managing Water in the West

Design Standards No. 13

Embankment Dams

Chapter 21: Water Removal and Control: Dewatering and Unwatering Systems

Phase 4 Final

U.S. Department of the Interior
Bureau of Reclamation

September 2014

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Design Standards Signature Sheet

Design Standards No. 13

Embankment Dams

DS-13(21): Phase 4 Final
September 2014

Chapter 21: Water Removal and Control: Dewatering and Unwatering Systems

Foreword

Purpose

The Bureau of Reclamation (Reclamation) design standards present technical requirements and processes to enable design professionals to prepare design documents and reports necessary to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. Compliance with these design standards assists in the development and improvement of Reclamation facilities in a way that protects the public's health, safety, and welfare; recognizes needs of all stakeholders; and achieves lasting value and functionality necessary for Reclamation facilities. Responsible designers accomplish this goal through compliance with these design standards and all other applicable technical codes, as well as incorporation of the stakeholders' vision and values, that are then reflected in the constructed facilities.

Application of Design Standards

Reclamation design activities, whether performed by Reclamation or by a non-Reclamation entity, must be performed in accordance with established Reclamation design criteria and standards, and approved national design standards, if applicable. Exceptions to this requirement shall be in accordance with provisions of *Reclamation Manual Policy*, Performing Design and Construction Activities, FAC P03.

In addition to these design standards, designers shall integrate sound engineering judgment, applicable national codes and design standards, site-specific technical considerations, and project-specific considerations to ensure suitable designs are produced that protect the public's investment and safety. Designers shall use the most current edition of national codes and design standards consistent with Reclamation design standards. Reclamation design standards may include exceptions to requirements of national codes and design standards.

Proposed Revisions

Reclamation designers should inform the Technical Service Center (TSC), via Reclamation's Design Standards Website notification procedure, of any recommended updates or changes to Reclamation design standards to meet current and/or improved design practices.

Chapter Signature Sheet
Bureau of Reclamation
Technical Service Center

Design Standards No. 13

Embankment Dams

Chapter 21: Water Removal and Control: Dewatering and Unwatering Systems

DS-13(21):[1] Phase 4 Final
September 2014

Chapter 21 – Water Removal and Control: Dewatering and Unwatering Systems is a new chapter within Design Standards No. 13 and includes:

- Water Removal and Control Applications for Embankment Dams
- Dewatering, Unwatering, Pressure Relief and Seepage Control Methods
- Considerations During the Design Process, and Data Collection and Hydrogeologic Parameter Development
- Considerations During the System Design, Installation, and Operation and Performance Processes

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[1] DS-13(21) refers to Design Standards No. 13, chapter 21.

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Water Removal and Control: Dewatering and Unwatering Systems

21.1 Introduction

21.1.1 Purpose

Construction of many conventional water projects such as dams, dikes, canals, siphons, and pumping plants requires some degree of excavation, which often extends below the local water table. The excavation can be an expensive operation, depending on the required depth, subsurface materials, and groundwater conditions. Water Removal and Control (WR&C) systems are often employed along with other techniques such as unwatering methods and/or cutoff walls in controlling the water and seepage within and surrounding the excavations. WR&C systems can be constructed by a variety of methods, either singly or in combinations, to effectively remove and control groundwater to facilitate excavation and construction activities "in the dry"[2] and to maintain stability of excavated slopes. Effective WR&C systems are also important to construction scheduling and safety of the construction crews, downstream populations and infrastructures, and the safety of the embankment dam itself.

21.1.2 Scope

Design of WR&C systems should rely as much on experience as on the theory and calculations. Each site is unique, and no two systems will be exactly alike. Additionally, there is no one correct design, although some designs may be more applicable than others to specific site conditions. A well-suited design may include multiple features employing different technologies and configurations to achieve the desired goals.

This chapter is intended to provide general guidance as to when dewatering should be considered and when a WR&C professional/specialist should be included as part of the design team. This chapter is also intended to acquaint design engineers with the types of data that a WR&C specialist requires to assist with design, as well as what types of support the specialist can provide.

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[2] The term "in the dry" does not have a formal definition; as used in excavation and construction applications, it means that the soils and/or sediments are relatively free of liquids and moisture such that the excavation is stable, the floor of the excavation forms a firm foundation for constructed facilities (footings, walls, slabs, etc.), and construction activities can proceed without being impeded by 'wet' conditions.

WR&C, as used in this chapter, is a generic term that refers to any system designed to remove and/or control groundwater and/or surface water at a site. WR&C systems can consist of dewatering and/or unwatering components. Dewatering system is a specific term that refers to any system designed to remove or control groundwater in and around a construction site. Unwatering system is a specific term that refers to any system designed to remove or control surface water or seepage water.

This chapter is intended to present general design considerations for the most widely used types of dewatering and unwatering systems currently accepted as viable alternatives for the removal and control of groundwater for activities related to embankment dams and related structures. Detailed design criteria have been included when appropriate. However, in keeping with the purpose of this chapter, emphasis has been placed on providing general considerations and information that will assist the designer in developing the most cost-effective design for a given site. It does not include specific information on how to design or evaluate WR&C systems. Selected references are provided for more in-depth specific discussions on how to design and evaluate WR&C systems.

This chapter assumes that the WR&C system designer has a firm understanding and experience in the theory and application of hydrogeologic concepts and practices. Accordingly, basic concepts of groundwater flow, well hydraulics, and well design will not be elaborated upon, except as applicable to illustrate a point. For detailed and more in-depth discussions of basic hydrogeologic concepts, the reader is referred to these cited references (Powers et al., 2007; Sterrett, 2007), as well as other applicable references cited in this report.

Use of trade names or company names are for illustrative purposes only and do not constitute an endorsement by the Bureau of Reclamation (Reclamation) or the United States Government.

21.1.3 Deviations from Standards

Where specific design criteria or standards are provided in this chapter, the design of WR&C systems within Reclamation must conform to these standards. If deviations from the standards are made, the rationale for not using the standard must be presented in the technical documentation for the WR&C system design. Technical documentation must be approved by appropriate line supervisors and managers.

21.1.4 Revisions of Standard

This design standard will be revised periodically as needed. Comments should be forwarded to the Bureau of Reclamation, Technical Service Center, Attn: 86-68300, Denver, Colorado, 80225.

21.1.5 Applicability

The guidelines presented in this chapter should be applied to dewatering systems used for removal and control of groundwater in and around embankment dams and related structures, either as permanent installations or as temporary installations, to facilitate excavation and construction activities. Examples include the use of dewatering systems to control flow or uplift pressures beneath or around a hydraulic structure. Use of dewatering systems to contain and isolate hazardous waste is beyond the scope of these guidelines.

21.2 Acronyms and Definitions/Terminology

21.2.1 Acronyms

ASTM	American Society for Testing Materials
CEAP	Construction Emergency Action Plan
cfs	cubic feet per second
COR	Contracting Officer’s Representative
CPT	Cone Penetrometer Test
DDR	Design Data Request
EAP	Emergency Action Plan
EPA	United States Environmental Protection Agency
FER	Field Exploration Request
FIBC	flexible intermediate bulk container
ft	feet
ft/s	feet per second
gpm	gallons per minute
l	length
L-23	CEAP Instrumentation Report
m	meters
mm	millimeters
O&M	operation and maintenance
ppm	parts per million (equivalent to milligrams per liter)
psi	pounds per square inch
PVC	polyvinyl chloride
Reclamation	Bureau of Reclamation
SI	International System of Units
SPT	Standard Penetration Test
t	time
TDH	total dynamic head
TSC	Technical Service Center (of the Bureau of Reclamation)
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey

WR&C	water removal and control
ºC	degrees Celsius
3D	three dimensional

21.2.2 Definitions/Terminology

All definitions, unless otherwise noted, are from Sterrett (2007). Commentary and/or amplifying information is provided in *italics*.

Anthropogenic: Created by people or caused by human activity *Collins English Dictionary – Complete and Unabridged (*Harper-Collins Publishers, 2003).

Aquifer: A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield economical quantities of water to wells and springs. Aquifers store and transmit water.

Aquifer test: A test involving the withdrawal of measured quantities of water from, or addition of water to, a well and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or addition (Driscoll, 1995):

An aquifer test is also commonly referred to as a pump test, pump out test, pumping test, or water test which may or may not be equivalent terminology. Aquifer tests may be short duration slug tests, a step test lasting several hours or up to a day, and long duration (several days to typically a week, but potentially up to several months) constant rate tests.

Artificially developed well: see "*Well development"*

Bail test: The instantaneous removal of a known volume of water from an open well while recording the drop in the static water level and recording the recovery of the water level over time as the water level returns to static, or near static, conditions.

The definition uses the term "instantaneous removal," and the analysis of bail tests assumes "instantaneous removal"; however, in practical usage, the removal of water is not instantaneous but should be "very rapid" or "near instantaneous."

Cone of depression: A depression in the water table or potentiometric surface that has the shape of an inverted cone and that develops around a well from which water is being withdrawn. This defines the area of influence of a well (*synonymous with zone of influence).*

Confined aquifer: A formation in which the groundwater is isolated from the atmosphere at the point of discharge by impermeable geologic formations. Confined groundwater generally is subject to pressure that is greater than atmospheric.

The confining unit does not necessarily have to be impermeable; rather, it just has to have a lower permeability than the underlying and overlying units. In the old nomenclature, a confining unit is referred to as an "aquitard" or "aquiclude."[3]

D_x nomenclature: The D_x (also d_x) nomenclature refers to the grain diameter (***D*** *or* ***d***) where x% of the sediment/material is finer – often referred to as x% passing when discussing sieve analyses (also called gradation analyses).

Some authors and/or numerical equations refer to D_x *as x% retained, which is the same diameter as* D_{100-x} *passing. It is important to know which nomenclature (% passing or % retained) is being used in discussions or is required in equations. In the absence of any clear statement as to whether it is % passing or % retained, it is not appropriate to assume one or the other. When referring to the "effective size" with a specified % passing or retained, then* D_e *(see "Effective size," below) is used. A bolded lower case "**d**" is sometimes used in place of a bolded upper case "**D**."*

Dewatering: The removal of groundwater or seepage from below the surface of the ground or other constructed surfaces, and the control of such water (Bureau of Reclamation, 1995, pg. 552).

Dewatering systems: Generally refers to any system of wells and/or well points along with the associated pumps, headers, discharge manifolds, power supply, and other appurtenances necessary to remove and control groundwater within a specific area. In common usage, it often includes temporary unwatering equipment and systems. As used in this chapter, it refers to any system or components specifically designed and installed to remove groundwater.

Eductor (*also eductor-jet pump or jet pump*): A type of pump where the energy from one fluid (liquid or gas) is transferred to another fluid via the Venturi effect. As the fluid passes through a tapered jet, kinetic energy increases and pressure decreases, drawing fluid from the suction into the flow stream. (Power, 1993)

Effective size - D_e *(also known as effective diameter, effective grain size, or effective particle grain size):* Defined by Hazen (1893) as the particle size where 10% of the sediment is finer (10% passing) and 90% of the material is coarser (90% retained), except where used as noted by other authors. D_e is not the same as D_{10}.

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[3] Aquitard (subsurface material that retards the flow of a liquid) and Aquiclude (subsurface material that excludes the flow of a liquid) have been replaced by the term "confining bed."

Filter pack (*also sand pack or gravel pack*): Sand or gravel that is smooth, uniform, clean, well rounded, and siliceous. The pack material is placed in the annulus of the well between the borehole wall and the well screen to prevent formation material from entering the screen.

Hydraulic conductivity - *K*: The capacity of a geologic material to transmit water. It is expressed as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Units of ***K*** are [*l*/t] (length/time). (United States Geologic Survey, 1923)

L-23: A Reclamation report that lists specific monitoring instruments referenced in the Construction Emergency Action Plan (CEAP) that are used by the contractor and by Reclamation to monitor the project during construction. The L-23 will include a schedule for reading the instruments, as well as a protocol for readings that are outside the allowable parameters (e.g. high water pressures, excessive deformations, etc.). (See section 21.7 of this chapter.)

Naturally developed well: see "*Well development*"

Permeability - *k*: The property or capacity of a porous rock, sediment, or soil for transmitting a gas or fluid, including water. Also a measure of the relative ease of fluid flow under unequal pressure. Units of permeability are the *darcy* [l^2] or, more commonly, the *millidarcy* (1 darcy is approximately equal to $10^{-12}m^2$).

Unlike hydraulic conductivity, permeability is time independent and applies to any gas or fluid, whereas hydraulic conductivity is time dependent and only applies to water.

Porosity - *ρ*: The percentage of the bulk volume of a rock or soil that is occupied by interstices, whether isolated or connected. Also shown as η in some equations.

Potentiometric surface: An imaginary surface representing the total head of groundwater in an aquifer that is defined by the level to which water will rise in a well.

Primary permeability (matrix permeability): Refers to the flow in primary pore spaces in a rock (Reynolds, 2003).

Pump test, pumping test, pump out test: see "*Aquifer test*"

Quasi three-dimensional (3D) model: In a quasi-3D model, one or more of the model layers of a full 3D model are not simulated. However, the vertical conductivity of the nonsimulated layer(s) is still used to calculate the conductance between the bounding (overlying and underlying) simulated layers. Flow through the nonsimulated layer(s) is assumed to be completely vertical. If the conductivity of the nonsimulated layer(s) is significantly lower than the conductivity of the bounding layers by several orders of magnitude or more, then the assumption of only vertical flow through the nonsimulated layer(s) is sufficiently accurate for modeling purposes (U.S. Geological Survey, 2014)

Radius of influence - $\mathbf{R_o}$: The radial distance from the center of a well to the point where there is no lowering of the water table or potentiometric surface (the edge of the cone of depression). $\mathbf{r}_o$ or r_o are sometimes used in place of $\mathbf{R}_o$ in equations.

Secondary permeability (fracture permeability): The flow in cracks or breaks in the rock (such as fractures, solution cavities, layering, etc.). These cracks or breaks do not change the matrix permeability, but they do change the effective permeability of the flow network (Reynolds, 2003).

Slug test: The instantaneous addition of a known volume of water (the slug) into an open well at static water level and recording the dissipation of the slug over time as the water level returns to static conditions. Slug test is also used as a generic term for any test in a single well that involves the instantaneous addition and/or removal (see "*Bail test"*) of water.

The definition uses the term "instantaneous addition," and the analysis of bail tests assumes "instantaneous addition"; however, in practical usage, the addition of a slug of water is not instantaneous but should be "very rapid" or "near instantaneous."

Specific capacity - $\mathbf{S_p}$: The rate of discharge of a water well per unit of drawdown, commonly expressed in gallons per minute per foot, or in cubic meters per day per meter. S_p varies with duration of discharge.

By itself, S_p is not a critical parameter for dewatering design. However, it is a useful parameter for designing the dewatering capacities of wells. In addition, it is a quick and easy field measurement that can indicate potential problems with a specific pumping well, resulting in reduced production. As drawdown increases, the S_p will generally decrease.

Specific retention - $\boldsymbol{S}_\mathbf{r}$: The ratio of the volume of water that a given body of rock or soil can hold against the pull of gravity to the volume of the body itself. It is usually expressed as a percentage.

The companion parameter to Specific Yield and together with Specific Yield equals the saturated porosity.

Specific storage - $\boldsymbol{S}_\mathbf{s}$: The volume of water released from or taken into storage from a unit volume of the porous medium per unit change in head. Units of [1/l] (1/length). (ASTM, 2011).

Change in storage results from the compressibility of the aquifer framework and the compressibility of water.

Specific yield - S_y: The ratio of the volume of water that a given mass of saturated rock or soil yields by gravity to the volume of that mass. This ratio is expressed as a percentage (see figure 2.5 in Sterrett, 2007).

The companion parameter to Specific Retention and, together with Specific Retention, equals the saturated porosity.

Specific yield is a function of the grain size, grain shape, and gradation of the rock or soil material, and is independent of head. As such, it can be related to hydraulic conductivity, which is a function of the same characteristics displayed in figure 21.2.1-1. The general relationship between Specific Yield, Specific Retention, Porosity, and Effective (Grain) Size is displayed in figure 21.2.1-2. Specific Yield is determined from laboratory testing of undisturbed core samples.

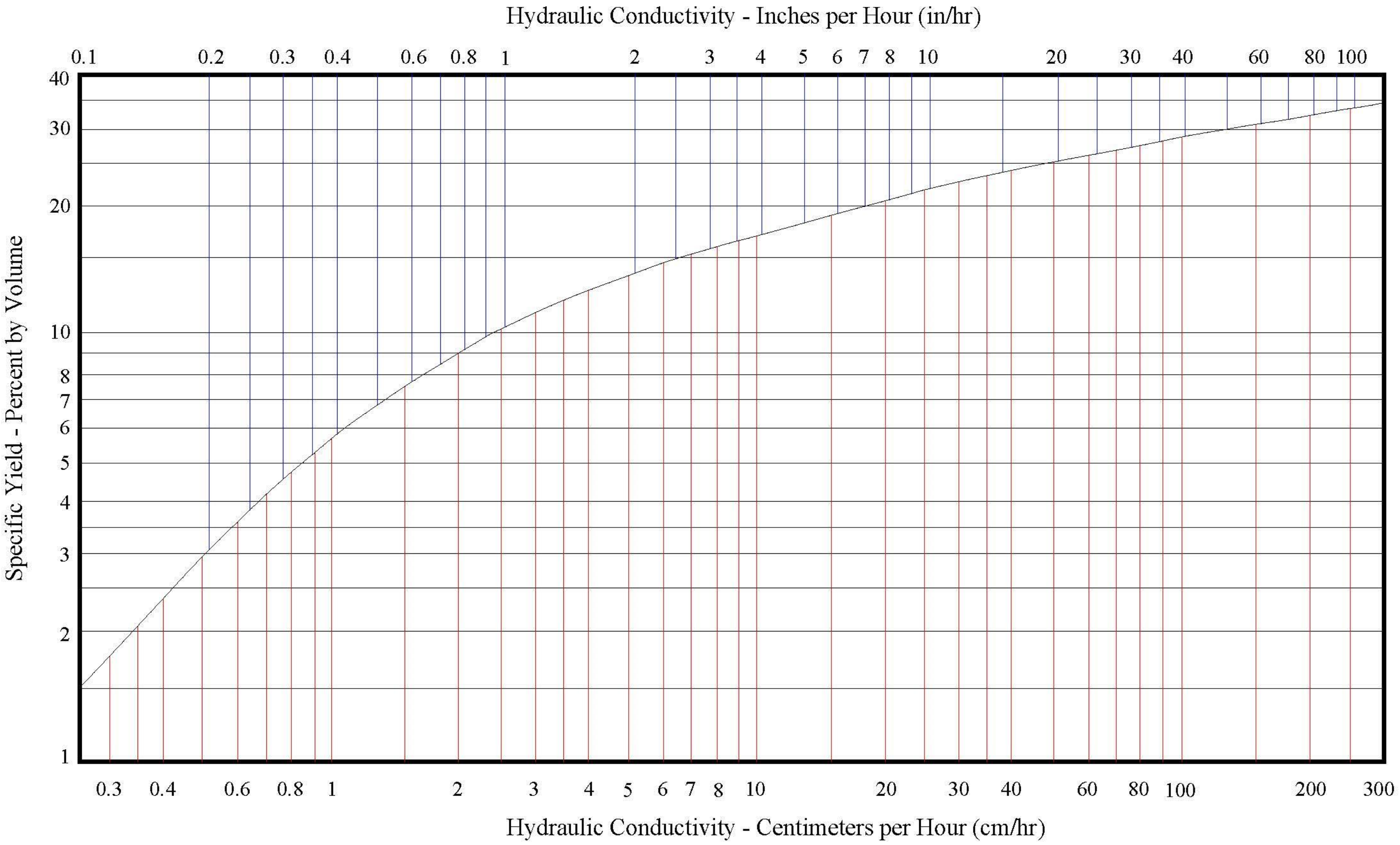


Figure 21.2.1-1 General relationship between Specific Yield (S_y) and Hydraulic Conductivity (*K*) (modified from Bureau of Reclamation, 1993).

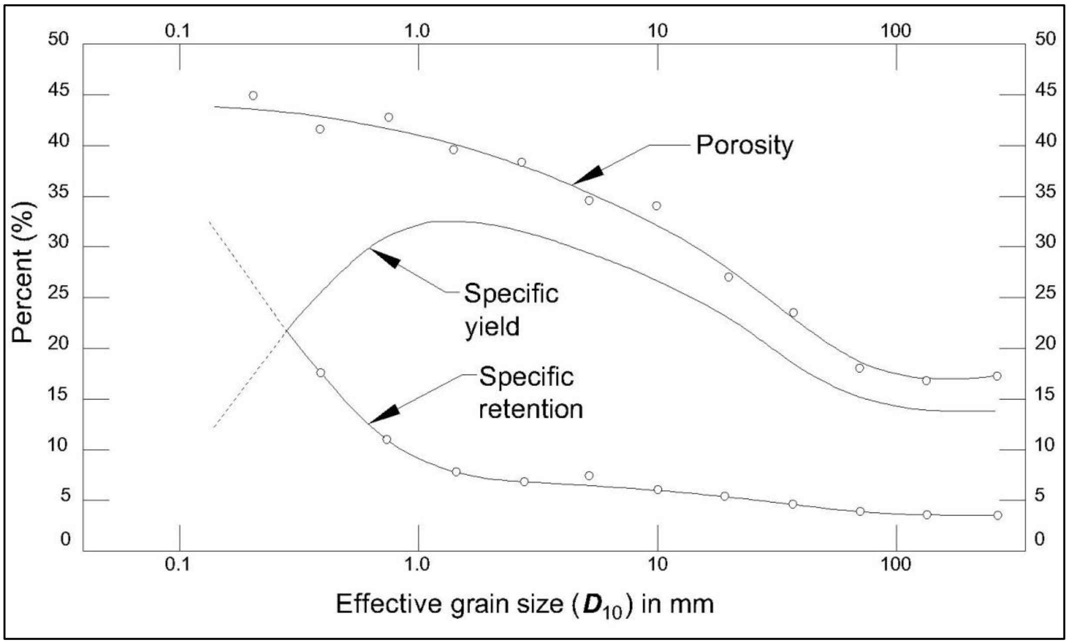


Figure 21.2.1-2 Relationships between Specific Yield (S_y), Specific Retention (S_r), Porosity (ρ), and effective grain size (D_{10}) (modified from U.S. Army Corps of Engineers [USACE], 2004).

Storativity – *S* (coefficient of storage): The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. (***S***, when representing storativity, is italicized and bolded)

*In an unconfined aquifer, the hydraulic head is expressed as the water table. The release of water from storage comes from the dewatering of the aquifer material, and storativity values are normally around 0.2 (**S** is dimensionless, when units of dimension are typically shown in equations, empty square brackets* [ ] *are used to denote that there are no units of dimension associated with **S**).*

*In a confined aquifer, the hydraulic head is expressed as a potentiometric surface above the top of the saturated aquifer material. The release of water from storage comes from the expansion of the water under reduced pressure and compression of the aquifer matrix under increased effective stress. Storativity values are on the order of 0.005 to 0.00005 (**S** is dimensionless). When the potentiometric surface is lowered to the level of the top of the saturated confined aquifer, the aquifer is no longer confined, and continued release of water from storage must come from drainage of the aquifer materials.*

Three-dimensional (3D) model: A numerical model in which parameters are simulated in all three physical dimensions, namely length, width, and height or x, y, and z respectively in numerical modeling Cartesian coordinate system.

Transmissivity - *T*: The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity values are given in gallons per minute through a vertical section of an aquifer 1 foot wide, extending the full saturated height of an aquifer under a hydraulic gradient of 1 in the U.S. customary system.

The International System of Units (SI) defines transmissivity in cubic meters per day through a vertical section of an aquifer 1 m wide and extending the full saturated height of an aquifer under a hydraulic gradient of 1.

*Transmissivity (**T**) is also defined as the hydraulic conductivity times the saturated thickness. In an unconfined aquifer, **T** will vary as the aquifer materials are dewatered and will vary laterally with the cone of depression of a pumping well. In a confined aquifer, **T** is relatively constant as long as the aquifer is essentially homogeneous on a regional scale and remains under confined conditions; otherwise, it responds as an unconfined aquifer.*

In highly transmissive materials, the cone of depression will be shallow but very wide, while in low transmissive materials (all other factors being equal), the cone of depression will be narrow but deep.

Two-dimensional model: A numerical or analytical model that simulates or evaluates physical parameters in two of the three physical dimensions, either length-width (x-y), length-height (x-z), or width-height (y-z).

Unconfined aquifer: An aquifer where the water table is exposed to the atmosphere through openings in the overlying materials or one where the upper surface is at atmospheric pressure.

Uniformity coefficient – *C*u: A numerical expression of the variability in particle sizes in mixed natural soils, *or engineered filter packs*, defined as the ratio of the sieve size in which 40% (D_{40}) (by weight) of the material is retained to the sieve size in which 90% (D_{90}) of the material is retained.

In terms of being consistent with the definition of D_x *(See "*D_x *nomenclature," above) it is the ratio of* D_{60} *(passing) divided by* D_{10} *(passing).*

Unwatering: The removal of ponded or flowing surface water and the control of such water (Bureau of Reclamation, 1995, pg. 552).

Unwatering systems: No formal definition; however, it generally refers to any system of drains, sumps, trenches, levees, and open pumping along with the associated pumps, headers, discharge manifolds, power supply, and other appurtenances necessary to remove and control ponded or flowing surface water within a specific area. As used in this chapter, it refers to any system or components specifically designed and installed to remove and/or control surface water.

Vadose zone: The zone containing water under pressure that is less than that of the atmosphere, including soil water, intermediate vadose water, and capillary water.

Water removal and control – WR&C: No formal definition; it is used herein to refer to dewatering and/or unwatering in general terms when there is no direct or implied reference specifically to dewatering or unwatering components, systems, or activities.

Water removal and control specialist: Qualified and experienced person charged with the responsibility to design, install, test, operate, maintain, monitor, and remove WR&C systems and/or system components. The specialist may be the same person or persons for the duration of the entire project, or the personnel may change for different phases of the WR&C activities such that one specialist may design the WR&C system(s); a second specialist may oversee the installation and testing of the systems; a third specialist may oversee the operation, maintenance, and monitoring of the system; and a fourth specialist may oversee the removal or abandonment of the systems at project completion.

Water table: The surface between the vadose zone and the saturated zone. That surface of unconfined groundwater at which the pressure is equal to that of the atmosphere.

Water test: see "*Aquifer test*"

Well point: A short length of well screen attached to the lower end of the casing. The casing and well points are driven to the desired depth within a shallow aquifer. A forged steel point is attached to the lower end of the well point to facilitate penetration.

Well development: Well development can be either artificial or natural when referring to the material in the filter pack. Artificial refers to a graded granular filter material placed in the annular space between the well screen and the borehole wall. Natural refers to a filter pack that is developed from native materials that are allowed to cave against the well screen.

Well screen: A filtering device used to keep sediment from entering a well.

21.3 Water Removal and Control: Applications for Embankment Dams

21.3.1 General

Embankment dams are frequently founded on alluvial deposits that consist of layers of varying thickness of coarse sand and gravel, silts, or clays before bedrock is reached. Embankment dams typically employ cutoff trenches, cutoff walls, or combinations of these in foundations consisting of permeable materials to control seepage and/or lengthen the seepage path under the dam. Foundation dewatering may be required to construct cutoff trenches and/or cutoff walls. Foundation dewatering is almost always required for modification construction activities on the downstream side of an existing dam, especially when the reservoir is to retain impounded water during construction.

Inadequate control of groundwater seepage and surface drainage during construction can cause major problems in maintaining stable excavated slopes and dry foundation surfaces. As stated in the *Earth Manual* (Bureau of Reclamation, 1990a, pg. 245):

> “The purpose of dewatering is to permit construction in the dry and to increase the stability of excavated slopes . . . Usually, dewatering consists of drains, drains with sumps, deep wells, and wellpoints either alone or in combinations for maximum effectiveness. Dewatering shall maintain a sufficiently low water table to allow for satisfactory excavation and backfill placement. Dewatering systems must be carefully designed to ensure the adequacy of the system.”

Seepage analysis and its control are discussed in more detail in *Design Standards No. 13 – Embankment Dams*, Chapter 8, “Seepage,” (Bureau of Reclamation, 2014a) and will be referenced as appropriate.

WR&C systems often are the only method needed to effectively remove and lower groundwater for excavation and construction activities. However, under some circumstances, the use of cutoff walls, sheet pile walls, cofferdams, and other constructed barriers to water movement can significantly improve the effectiveness of the WR&C operations, while reducing the size and/or duration of operation of the overall WR&C system.

In some circumstances, WR&C systems may be required for the long-term control of groundwater as part of the permanent Operation and Maintenance (O&M) program at specific dam sites. In this case, the design of the WR&C system would require greater detail and attention to local groundwater conditions, source areas, discharge areas, local and regional hydrologic characteristics, gradients, and seasonal variations than are discussed in this chapter.

21.3.2 Design and Contracting Considerations

Sometimes performance-based specifications are written for a contractor to design and install the WR&C system under Reclamation standards. The advantage of contractor designs is to allow contractors to employ their own specialized systems at a lower bid cost. A major disadvantage of contractor designs is that the contractor that wins the bid may have minimized the dewatering plan or made nonconservative or incorrect assumptions in its design. Since dewatering/unwatering can be a significant portion of the construction costs with a significant degree of uncertainty, a large number of lowest bid proposals have historically had nonconservative designs. For projects that especially depend on the success of the WR&C system (such as where public safety or the safety of construction personnel is at stake, safety of the dam, time-critical projects, etc.), it is recommended that the WR&C system be designed by Reclamation. Reclamation has considerable experience with designing WR&C systems, and it is recommended that specifications use Reclamation-designed systems whenever possible to reduce or minimize claims, construction delays, and cost overruns.

In the event that the WR&C system is anticipated to be complicated, or where there is significant risk involved with the implementation and successful operation of the system, it is recommended that the specifications include a Reclamation-designed system and that the WR&C specialist develop and provide the contract specifications for the WR&C system. If it is considered advantageous to the Government to have the contractor design the WR&C system, the specifications should provide a section for discussion of the design, required design elements, and required performance goals. The WR&C specialist will provide a technical review of the contractor designed WR&C system through the submittal process.

Possible reasons for using a contractor-designed WR&C system would include:

- If the contractor will be able to employ proprietary methods or the dewatering would be deeply integrated into the construction activities
- If the dewatering is simple and not highly critical to construction or dam safety
- If the contractor-designed WR&C system would result in significant cost savings, reduced construction time, and/or the failure of the dewatering system would pose minimal risk to the safety of the dam, the dam structures, or the population at risk

Even if a contractor designs the WR&C system, Reclamation must also independently design a system for the purposes of cost estimating and evaluating bid documents or technical proposals. All of the data necessary for a good Government-designed WR&C system would need to be acquired during design.

For contractors who are to include the design of a WR&C system in their bid, the information required for design, including geologic logs, pump test results, and lab test results, can be summarized by the WR&C specialist and should be included in the contract documents, or time needs to be allowed in the contract for the contractor to obtain the necessary data. WR&C can be a prime source of claims from contractors, so an appropriate amount of good design data is always necessary for any project in which WR&C is an integral part.

Additionally, the Reclamation design team, including the WR&C specialist, must identify the Federal, State, and/or local agencies that will have regulatory jurisdiction of the project, determine which regulations will impact the project, and determine what Federal, State, and/or local permits will be required. The design team must also decide which, if any, of the permits will be obtained by Reclamation, and which permits will be the contractor's responsibility to obtain.

21.3.3 Performance Considerations

Effective WR&C systems fully penetrate pervious strata where practical. Partially penetrating systems can be designed to effectively remove and control water in the excavation footprint; however, the size and complexity of the system may become prohibitively expensive to install and operate. Partially penetrating systems in pervious strata are often used as a control measure to depressurize and/or dewater specific highly pervious zones within the excavation footprint.

WR&C systems can be designed to desaturate unconsolidated materials in the foundation areas of embankment dams to provide stable cut slopes and 'in-the-dry' working conditions within an excavation, and/or to depressurize strata below the excavation footprint. Specific site conditions often determine the complexity and types of WR&C systems that are suitable for a site. Systems should be capable of achieving and maintaining the desired amount of desaturation and/or depressurization over the period in which construction activities occur and include an adequate capacity during extreme hydrologic events that may occur, such as periods of heavy rain or when a reservoir is full. A system that barely meets the minimum required capacity during most of the year could easily become ineffective under extreme conditions. These extreme conditions should be determined prior to design and may become the critical design parameter for the system.

WR&C systems are often used for reducing uplift pressures in fine-grained strata or bedrock below the excavation footprint. The WR&C system, when used to depressurize saturated strata below the excavation footprint or behind a cut slope to provide stability, can provide short-term or long-term depressurized conditions for O&M after construction is complete. The WR&C system design should take into consideration how critical certain components are to the safety of the embankment dam, and appropriate design redundancy should be included.

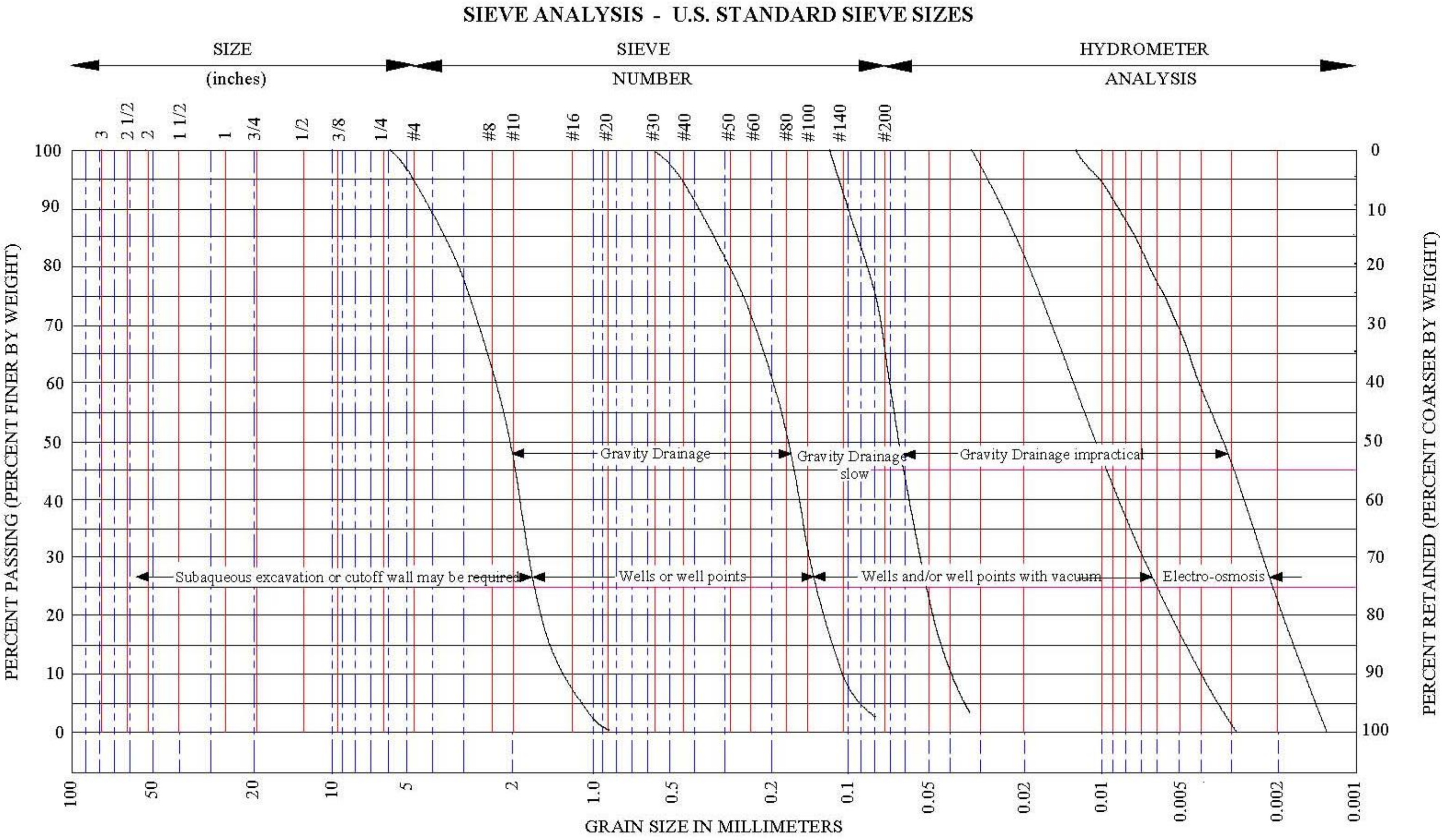
21.4 Water Removal and Control: Dewatering, Unwatering, Pressure Relief, and Seepage Control Methods

21.4.1 General

The choice of a WR&C method is determined by local geologic and hydrologic conditions (figure 21.4.1.1), the reason for dewatering (table 21.4.1-1), the type of equipment readily available, and the associated costs. Another major consideration for the type of system selected is the duration of operation of each of the components of the system and the conditions under which each component must operate.

The experience of the WR&C specialist and dewatering contractor plays a significant role in the WR&C methods selected, as well as costs and construction constraints. The WR&C specialist's main role is to assist the design team in selecting system components that provide adequate flexibility for site conditions based on past experience. The WR&C specialist can ensure that an adequate design is provided which has alternative methods built in for reaching dewatering goals if extreme conditions are encountered.

Driscoll (1995) lists the two most important considerations in the design of a dewatering system as storativity and transmissivity because these factors control the volume of groundwater in the area to be dewatered and the rate at which it can be removed. Later authors (Sterrett, 2007; Powers et al., 2007) have added additional items to the "important considerations" identified by Driscoll. Under specific or unique conditions, any one of the items, or combination of items, may be more important than the others. Important considerations are presented at appropriate points throughout this chapter.



GRAVEL		SAND			SILT or CLAY
Coarse	Fine	Coarse	Medium	Fine	

USA-COE Classification TM 5-815-5/AFM 88-5, Chap 6/NAVFAC P-418

**	GRAVEL	SAND			SILT	CLAY
		Coarse	Medium	Fine		

ASTM Standards D422-63; D643-78 ** Cobbles

GRAVEL	SAND					SILT	CLAY
	V. Coarse	Coarse	Medium	Fine	Very Fine		

US Dept of Agriculture, Agriculture Handbook No. 436 (1975)

GRAVEL (Pebbles)						SAND					SILT				CLAY	
**	V. Coarse	Coarse	Medium	Fine	V. Fine	V. Coarse	Coarse	Medium	Fine	V. Fine	Coarse	Medium	Fine	V. Fine	Coarse	Medium

Modified Wentworth Scale - after Lane, et al., 1947 ** small cobbles

Figure 21.4.1-1. Practical limits of dewatering methods/technologies for different unconsolidated materials (adapted and modified from, Bureau of Reclamation, 1995; USACE, 2004; AGI, 1982; and Powers et al., 2007).

Table 21.4.1-1. Groundwater Removal and Control: Methods and Applications

Method (chapter section and section title)	Application	Remarks
21.4.2 (1) Deep Extraction Well System (dewatering)	Dewater materials that can be gravity drained; usually for large and/or deep excavations	Can be installed early for predewatering; capable of wide range of capacities
21.4.2 (2) Well-point System (dewatering) 21.4.3 (5) Well-points (unwatering) 21.4.5 (1) Well-points (seepage control)	Dewater shallow soils that can be gravity drained; unwater slow draining, finer grained, shallow soils	Commonly used in shallow excavations or staged excavations; limited to about 15 feet (ft) of drawdown per stage; installed quickly
21.4.2 (3) Eductor Systems (dewatering) 21.4.5 (2) Eductor Systems (seepage control)	Dewater soils that can be gravity drained; usually for deeper excavations where small flows are expected in finer grained materials	Effective to about 100 ft; requires significant amount of piping and a steady supply of water; can be connected to a vacuum system to enhance water removal
21.4.2 (4) Sumps (dewatering) 21.4.3 (1) Sumps (unwatering)	Dewater materials that can be gravity drained; usually for localized high water tables in the bottom of excavation	Can only lower the water table to within 1 ft or so of the bottom of the sump; sumping is generally most effective in well-drained, well-graded, partially cemented or porous soils or rock
21.4.3 (2) Ditches (unwatering) 21.4.5 (3) Ditches (seepage control)	Intercept, reroute, and remove water entering or ponding in an excavation	Water levels can only be lowered a few feet; passive system
21.4.3 (3) Drains (unwatering) 21.4.5 (3) Drains (seepage control)	Intercept, reroute, and remove water entering or ponding in an excavation	Water levels can only be lowered a few feet; passive system
21.4.2 (5) Vertical Sand Drains (dewatering)	Used to conduct water from upper strata to lower, more pervious strata	Dewaters upper, less pervious strata without having to screen the strata; not effective in highly pervious strata or upwards pressure gradients; slow process
21.4.3 (4) Open Pumping (unwatering)	Remove and control flowing or ponding surface water	Effective for intermittent removal of ponded water or surface flows such as runoff from rain events or snowmelt
21.4.4 (1) Pressure Relief Wells	Reduce and control artesian pressures below the construction excavation	Requires special design and construction to prevent cross connection between a lower and upper aquifer
21.4.4 (2) Vacuum Pressure Relief Wells	Reduce and control artesian pressures below the construction excavation	Vacuum increases gradients near the well point and increasing flows; little added benefit if lifts are over 15 ft in unconfined materials
21.4.5 (4) Filters and Seals (seepage control)	Restrict or eliminate surface seepage	Effective for small flows in discrete zones or locations
21.4.6 (1) - (4) Groundwater Cutoff Structures	Stop or minimize flows and/or seepage into excavation when installed down to impervious stratum	Very effective but depends on site conditions and method used; in situ methods susceptible to gaps in the cutoff wall

21.4.2 Types of Dewatering Systems

Commonly employed dewatering methods include those discussed below.

21.4.2.1 Deep Well System

A deep well system is a system of one or more deep wells, including horizontal wells, connected to a common or several separate discharge headers. "Deep" is a relative term. As used in this chapter, it means any well that operates below the depths commonly reached by well points and sumps.

21.4.2.2 Well-Point System

A well-point system is a vacuum system of one or more well point units where each unit consists of a series of well points connected to a common discharge manifold and a common well-point pump.

21.4.2.3 Eductor Well System (also Eductor-Jet Pump or Jet Pump)

An educator well system is a downhole vacuum system of one or more eductor well units where each unit consists of one or more eductor wells connected to a common pump system and a common discharge manifold.

21.4.2.4 Sumps

Essentially, a sump is a large-diameter, relatively shallow well in the excavation. Water levels can only be lowered to a point close to the bottom of the sump. Sumps are effective for lowering localized high water tables in relatively permeable materials, but they are not effective for large areas.

21.4.2.5 Vertical Sand Drains

Vertical sand drains consist of a vertical shaft or large-diameter borehole that is filled with a highly permeable material such as filter pack material, pea gravel, or coarse sand. The shaft or borehole penetrates an upper and lower water-bearing zone and the low permeability materials separating the water-bearing zones. This provides a passive, gravity-drainage conduit to dewater the upper water-bearing materials. This presumes that the lower water-bearing materials are not under artesian pressures.

21.4.3 Types of Unwatering Systems

Commonly employed unwatering methods include those discussed below.

21.4.3.1 Sumps

A sump is an excavated hole in which a perforated or slotted pipe is installed vertically, and the hole around the pipe is backfilled with coarse filter materials such as gravel or a gravel-sand mixture. A sump pump or trash pump is installed inside the vertical pipe, and accumulating water is removed as necessary.

21.4.3.2 Ditches

Ditches are shallow linear excavations that generally parallel a slope or area of seepage and drain into a sump or other low spot, where the collected water can be channeled out of the construction excavation. Ditches are typically filled with gravel or other coarse materials. Where erosion or sloughing of the ditch banks is anticipated, they can be lined with a geofabric or geomembrane before being filled with gravel. Ditches are commonly unwatered with a sump pump.

21.4.3.3 Drains

Drains are open or closed, shallow or deep, linear trenches (closed drains incorporate a perforated pipe (French drain) placed on a bed of gravel or other porous medium before backfilling) that are backfilled with a gravel-sand mixture and covered with native materials excavated from the trench. Drains are connected to a sump or can simply drain to the surface if they are installed on a slope.

21.4.3.4 Open Pumping

Open pumping consists of removing localized standing or ponded water, as needed, by using a trash pump or “dirty”[4] water pump. Open pumping differs from a sump in that the pump is not placed in an excavated or prepared sump; rather, it is placed in a low spot on the surface where water temporarily ponds. As such, the pump can be moved across the site from low spot to low spot as needed.

21.4.3.5 Well Points

Well points are used where a large (often uneven) area requires unwatering or where open pumping may remove too much suspended sediments; a line or lines of well points may be installed along a seepage zone, or where water frequently ponds to remove the water and dry out the soils. Use of well points for unwatering would be a very shallow application of this method.

21.4.4 Types of Pressure Relief Systems

Commonly employed pressure relief technologies include those discussed below.

21.4.4.1 Pressure Relief Well

A pressure relief well is a permanent or temporary specialized deep well designed to reduce and control artesian pressures below the construction excavation. It is not necessarily designed to dewater the artesian aquifer; rather, it is designed to relieve artesian pressures and reduce hydraulic uplift pressures that could lead to localized or widespread heaving of the floor of the excavation.

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[4] Dirty water pumps, and trash pumps, are pumps designed to function with sediment laden water and/or debris up to 1 inch in diameter.

21.4.4.2 Vacuum Pressure Relief Well

A vacuum pressure relief well is a temporary pressure relief well with the capability of pulling a vacuum in the artesian aquifer to further increase yields in low conductivity materials and to compensate for loss of hydraulic gradient over time.

21.4.5 Types of Seepage Control Systems

Commonly employed localized seepage-control methods include those discussed below.

21.4.5.1 Well Points

Well-point systems are an effective means of controlling localized seepage flows by intercepting the water before it reaches the area of interest.

21.4.5.2 Eductor Systems

Eductors may be a suitable technology for localized seepage control depending on the conductivities of the materials within and through which the seepage waters are flowing, and the quantity of the seepage.

21.4.5.3 Ditches and Drains

Ditches and drains are effective for collecting localized seepage water and channeling it away from the construction zone.

21.4.5.4 Filters and Seals

Depending on the source of the seepage water and the pathways it takes to reach the seepage zone, surface filter materials or seals, such as injection grouting, may be a viable means of controlling localized seepage.

21.4.6 Cutoff Walls for Groundwater Control

Cutoff walls are sometimes used with dewatering and unwatering systems. Commonly employed cutoff walls for groundwater control include those discussed below.

21.4.6.1 Sheet Piles

Sheet piles are interlocking steel sheets driven into the ground and into underlying lower permeability strata to form a barrier to groundwater flow or to lengthen the flow path, thereby reducing the quantities and/or head of water that needs to be removed and controlled.

21.4.6.2 Slurry Trenches

Slurry trenches are trenches backfilled with a low-permeability slurry to inhibit groundwater flow or to lengthen the flow path similar to sheet piles. Slurries typically consist of a bentonite-cement mixture or a soil-bentonite mixture.

21.4.6.3 Secant Walls

Secant walls consist of a series of overlapping concrete-filled drill holes which form a barrier wall that is extended to a low-permeability stratum similar to the way sheet piles are driven into a low-permeability stratum.

21.4.6.4 Deep Soil Mixing

Deep soil mixing consists of a series of overlapping soil-cement columns created by using a large-diameter, hollow-stem auger system to create overlapping columns and inject cement down the hollow stem while extracting the auger, thereby mixing the soil and cement as the auger is withdrawn.

More detailed discussions of cutoff walls can be found in *Design Standards No. 13 – Embankment Dams,* Chapter 16, "Cutoff Walls" (Reclamation, 2015b; in revision).

21.5 Water Removal and Control: Design Process Considerations

21.5.1 General Description

Each level of the design and construction process of a project must include water removal and control considerations. This is due to the potential high costs of WR&C systems, impacts to the project schedule, and the importance of water removal and control to the success of the project construction and dam safety. An evaluation of project schedule impacts from a total or partial failure of the WR&C system should include the potential impacts to:

- The safety of the embankment dam during construction,
- The safety of the construction activities,
- The safety of personnel, including on-site personnel and the downstream Population At Risk personnel.

Thus, each element of the project that will require excavation for construction should be evaluated for the potential need for WR&C. Additionally, any element that will be constructed in or near wetlands, saturated soils, or areas with high water tables (even if excavation is not required) must be evaluated for the potential need for WR&C. Where site conditions warrant dewatering, collection of dewatering data is an integral and essential part of the design data package and must be given the required priority in funds, staffing, time, and personnel to minimize possible problems, such as expensive construction delays and contractor claims.

Design data for dewatering systems should be obtained concurrently with, and in coordination with, the design data for the feature to be constructed (chapter 4 of Reclamation, 2007a). In some cases, there are State or local design requirements for WR&C systems; these should be identified and incorporated into the project considerations at the feasibility design level. Where dewatering may have impacts from/to existing adjacent structures, facilities, or water resources, a study of the area surrounding the site may be necessary to determine and document potential impacts as an integral part of data gathering. Nearby structures should be thoroughly surveyed before dewatering systems are started, and their condition should be closely monitored during construction. A CEAP should include action plans for addressing any changes in the structures' condition(s).

Design of efficient and effective dewatering systems will require site-specific data (see chapter 4, section 9, "Wells" in Reclamation 2007a) that is not normally collected as part of the geological and geotechnical facility design data collection for dams. Accordingly, Reclamation WR&C specialists should be consulted for input when preparing a Field Exploration Request (FER) and the design data collection program, especially for such activities as foundation, site, and groundwater characterization. If there is existing monitoring instrumentation at the project site, the Instrumentation and Inspections Group at the Denver Technical Service Center (TSC) can provide a CEAP Instrumentation Report (L-23) that lists the locations, reading schedule, and other details of interest to collect valuable data.

Adequate surface and subsurface data appropriate to the level of design or critical nature of the construction project and the site conditions are essential to the proper design, installation, and operation of dewatering systems. The types of data, the amount of data, the areal coverage, and the completeness of the data are directly related to the site conditions, size and complexity of the features required, construction time, and other related factors. In some instances, the amount of data required for a dewatering system design may equal or exceed the foundation data required for design of the constructed feature.

The level of detail and the area of coverage of the required data should be appropriate for the anticipated dewatering requirements and dewatering system. For example, if aquifer tests are required, the test wells should approach the size and capacity of anticipated dewatering wells. Construction projects covering a large area where subsurface conditions are anticipated or expected to change would require multiple aquifer tests across the construction site. If appropriate, such facilities should be preserved and made available to prospective contractors for their testing and/or operational use.

21.5.2 Appraisal Level Design

At the appraisal design level, the focus of the project team is to determine the project Problems, Needs, and Opportunities. This process will generate a certain number of alternatives. For each alternative, the WR&C specialist should be involved to:

- Review the available geologic information, instrumentation data, and plan concept
- Discern potential dewatering requirements, extent, and viable systems
- Provide a general quantity estimate range for each of the viable WR&C systems
- Assist with the Design Data Request (DDR) by providing geologic data requirements and hydrogeologic data requirements that will be required for the final design

21.5.3 Feasibility Level Design

For the feasibility level, the project alternatives are delineated and better defined. The WR&C considerations are still preliminary because only limited geologic and hydrogeologic data are likely to be available to design a system.

Often, there will be a need to begin water removal and control operations well in advance of the construction activities, either because of the type of system that will be employed, type of subsurface materials to be dewatered, or because of operational constraints of the dam facilities. In such cases the dewatering activities may be under a separate contract and the WR&C system design may have to go to final design significantly ahead of the construction contract. Thus, collecting the necessary design data and completing the final design will be a critical path item in the overall Project Management Plan. Where there are State or local specific project or environmental design requirements, they should be included in the project considerations at this time.

Based on the project design drawings, geologic data, and hydrogeologic data, a WR&C specialist’s responsibility is to:

- Provide a conceptual WR&C system or systems for each appraisal level alternative that is selected to be carried forward to the feasibility level
- Develop quantity sheets for cost estimates

- Assist with the FER by providing geologic and hydrogeologic exploration requirements and specialized testing that will be required for the final WR&C design

In the case where the WR&C activities lead to a design that will be in a separate contract, the WR&C specialist's responsibilities include:

- Assist with field explorations and data collection by:
    - Assist with and/or identify requirements of soils testing for design parameters
    - Complete field testing (aquifer testing, etc.) and evaluate results or oversee these activities
- Provide final design
- Provide lead time estimates for consideration in developing the project schedule
- Prepare final quantity estimate sheets
- Prepare construction specifications and WR&C design parameter summary for inclusion in the contract documents.

The feasibility level is an excellent opportunity for ensuring that all the elements have been considered. Depending on the type of WR&C system used, there can be a significant lead time from the installation and beginning of dewatering until the groundwater levels are brought down to the required construction levels; capturing this in the project schedule is important. At this time, it is also important to determine the manner in which WR&C will be handled contractually (i.e., a contractor designed or Reclamation designed WR&C system), as well as to consider the longevity of the wells and monitoring instrumentation that will be installed because this will affect the design of those elements.

21.5.4 Final Design

In the case where the WR&C systems for final design are not completed in a separate contract, the WR&C specialist's responsibilities include:

- Review and synthesize the completed geologic explorations, including seepage and slope stability analyses
- Evaluate completed soils testing for design parameters
- Complete field testing (aquifer testing, etc.) and evaluate results

- Complete WR&C design in cooperation with geotechnical analyses and designs
- Provide WR&C lead time estimates for consideration in developing the project schedule
- Prepare final design drawings and specifications
- Prepare final quantity sheets
- Prepare construction specifications and WR&C design parameter summary for inclusion in the contract documents

21.5.5 Performance Considerations

For the contractor designed WR&C systems, the contractor's WR&C specialist or subcontractor will be responsible for the items in section 21.5.4. Reclamation's WR&C specialist will provide a technical review of the contractor's system prior to installation and will provide construction support to ensure that the system is functioning. Reclamation's WR&C specialist will be responsible for the items discussed in sections 21.5 through 21.8. Additionally, Reclamation's WR&C specialist will oversee any data collection identified in section 21.5.4 and prepare a final design and quantity estimate sheets for an Independent Government Cost Estimate

For Reclamation-designed WR&C systems, Reclamation's WR&C specialist will be responsible for the items discussed in section 21.5.4 above. The construction specification paragraphs will provide specifications for the installation and maintenance of the system. Reclamation's WR&C specialist will provide construction support to ensure that the system is installed in compliance with the specification and is functioning as designed.

21.6 Water Removal and Control: Data Collection and Hydrogeologic Parameter Development Considerations

21.6.1 General Description

Data collection and hydrogeologic parameters development is a multistep process involving:

- Problem Definition and Identification of Potential Critical Design Parameters

- Identifying Field Data Collection Needs and Preparation of FER Inputs
- Laboratory Testing
- Field Testing
- Critical Design Parameter Analysis

21.6.2 Problem Definition

The key elements of the project site's physical characteristics, the data needs to characterize the site, and a conceptual approach to meeting the project goals should be systematically identified. One such systematic approach is described in ASTM Standard 5979-96, *Standard Guide for Conceptualization and Characterization of Groundwater Systems* (ASTM, 2008).

Any systematic approach should include at least one site visit to build a conceptual model of the site and the project that identifies the characteristics and dynamics of the physical system including:

1. Main elements of the hydrologic system (surface water and groundwater)
2. Determine critical or controlling system processes
3. Determine acceptable simplifying assumptions for approximations
4. Determine critical system elements
   a. Processes
   b. Current state
   c. Stresses
5. Determine scale and dimensionality of processes
6. Determine external (nongroundwater) elements
   a. Processes
   b. Current state/conditions
   c. Stresses

The conceptual model will form the basic framework for determining the critical design parameters, designing a data collection program, analyzing the data, and developing the model. Many times on a project, the goal of feasibility level and final designs is to determine if more or less complex systems can be used effectively. Therefore, defining how each of these potential systems may work is a critical issue. Processes, current state, and existing conditions may be a range of values that are estimated for site conditions. As additional data is provided, adjustments to the applicable conditions can be made.

21.6.3 Defining Potential Critical Design Parameters

Based on the conceptual model, the critical design elements can be identified.

The WR&C specialist should first define a set of "testing criteria"[5] that will be used to identify if any element of the physical system is critical or noncritical to the design process and the goals of the project. The criteria will be unique to the site, the project, and the project goals, but it will usually fall into the following general categories:

1. Stability of natural, cut, and excavation slopes
2. Integrity of embankment dam and material zones within the dam
3. Depth and areal extent of dewatering
4. Impacts on, or from, construction activities and schedules
5. Impacts from external sources (extreme weather events, dam operations, etc.)
6. Public and worker safety
7. System efficiencies and cost effectiveness
8. Impacts to surrounding infrastructure(s)
9. Discharge water handling and quality

Systematic application of the criteria to the conceptual model will identify potentially critical elements, and the data needed to characterize and evaluate the critical elements can be itemized. Upon further refinement and data analysis, some of the potentially critical elements may turn out to be noncritical. It is always better to be conservative and have some potentially critical elements turn out to be noncritical than the reverse.

It should be emphasized that secondary permeability of any soil or rock may be the controlling factor in designing a WR&C system. For example, in materials

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[5] As used here, testing criteria refer to the type of tests or evaluations that will be used to identify and quantify the listed criteria, and the Quality Assurance/Quality Control procedures associated with the testing.

such as hard rock and weakly cemented sandstone/claystone that is fractured, the secondary permeability through fractures may be much greater than that of the primary permeability through the mass of the rock. This is even more important in ‘hard’ rock where secondary permeability can be orders of magnitude greater than the primary permeability. This can also be true for some silt and clay alluvial deposits. Therefore, the concept of secondary permeability should be considered when establishing a testing program. Fractures through dense strata may not be encountered in drill holes or intervals of field testing. Also, gradation and other lab tests may not reveal this information. Only site-wide mapping and large-scale field tests can attempt to identify and measure the secondary permeability of a subsurface unit.

21.6.4 Field Data Collection: Identifying Needs

Using the list of potentially critical elements and the data needed to characterize and analyze the elements as a guide, all relevant and pertinent existing data should be reviewed. Typical existing data categories include geologic studies and reports, water supply records, well logs, soil surveys, topographic data, flood zone maps, historical maps, utility maps, boring logs from other projects or nearby projects (dams, roads, bridge footings, buried utilities, etc.), and previous construction experience at the site or in the near vicinity. The goals of the review are to:

1. Collect, itemize, and tabulate existing information about the site and local conditions

2. Identify any potentially critical elements that can be reclassified as noncritical based on existing information

3. Generate a FER and DDR to fill in gaps in the existing data

Site reconnaissance is very beneficial to the WR&C specialist – particularly in regard to the generation of the conceptual model, but also afterwards to verify the conceptual model, to verify the potentially critical elements, and to lay out field exploration and data collection sites. Field data collection for water removal and control overlaps and compliments field data collected for geotechnical investigations. As such, close coordination between the geotechnical staff and the WR&C specialist can eliminate a lot of duplication of effort in collecting the design data necessary for both disciplines.

The following list of generalized site data is applicable to both geotechnical and hydrogeological investigations. At an appraisal level, some of these items may be conceptual or highly generalized. However, they will be refined through the field data collection activities and the design process leading from appraisal to final design.

21.6.4.1 General and Regional Information

1. Climatic data including temperature and precipitation, on a daily or other appropriate basis, for the nearest station for the period of record. Also, details, where appropriate, on the occurrence of severe storms and other similar events.

2. A preferred electronic format should be selected by the design team, and all spatial data should be entered into a common data base in the preferred format.

3. Plan map of the site and surrounding topography at an appropriate scale and contour interval.

4. Geologic map(s) and descriptions of the local and regional geology with cross sections, and the site-specific surface geology with cross sections and descriptions of materials including soils, colluvium, alluvium, landslide deposits, fill materials from previous projects (dams, roads, bridges, etc.), waste materials, and borrow areas

5. Plan map of the site including existing on and off site infrastructure such as roads, buildings, and underground and above ground utilities; political and jurisdictional boundaries, adjacent surface water features such as lakes, streams, and wetlands; previous explorations including locations of drill holes, test holes, piezometers, observation wells, test wells, test pits, and cross-section lines.

6. Where appropriate, stream flows and stages, lake or reservoir stage elevation, flood frequencies and stages, and other similar data for the period of record.

7. Planned or anticipated reservoir operations prior to and during construction.

21.6.4.2 Construction Plans

1. Excavation plan, including a plan map showing the excavation footprint, access routes, cut slopes, and staging area(s). At the appraisal level, this may only be conceptual or highly generalized.

2. Cross sections through the excavation showing excavated depths, variations in excavated depths, and excavated materials (embankment dam zones, foundations, bedrock, etc.).

3. Locations of potential settling pond(s), potential discharge points for production water from dewatering and/or unwatering system(s), and potential surface water control features (e.g., cofferdams, ditches, levees, etc.).

4. Construction sequencing including how long the excavation is anticipated to be open and when it will be open (what time of year or seasons).

21.6.4.3 Surface

Surface information shall include data that might reflect favorable or unfavorable conditions as to soil erosion or resistance, runoff, and the potential for mass movements and slope failure. Typical geotechnical investigations that are applicable and valuable for water removal and control design include:

1. Infiltration and permeability of surficial materials.
2. Gradation and density of cohesionless strata.
3. Presence of cobbles and boulders.

21.6.4.4 Subsurface

Subsurface information shall include data that provide site-specific and site-wide representative aquifer properties, areal distribution of relative conductivities and storage coefficients, location and strength of potential recharge sources and/or barriers, and known or anticipated seasonal changes in the groundwater system. Data from hydrogeologic investigations typically include:

1. Subsurface stratigraphy.

2. Logs of drill holes, test holes, piezometers, existing wells, and test pits with depths and thickness of materials, description of materials, and results of sample and in situ testing (field and/or lab testing).

3. Geologic mapping of the site and surrounding area including geologic cross sections that show vertical and lateral variations in materials encountered in drill holes, test pits, and any other subsurface investigations (Standard Penetration Test (SPT) logs, for example).

4. Results of material sampling including depths, descriptions, mechanical analyses, and hydrometer analyses.

5. Geophysical logs where appropriate.

6. Aquifer tests and other similar test results (e.g., slug tests) including layout of test holes, depths and design of wells and piezometers, tabulated test results including yields and drawdown with time, pre- and post-testing static water levels, and recovery data.

7. Analyses of aquifer tests or other similar test results including calculated or inferred hydraulic conductivity of stratigraphic layers.

8. Groundwater levels (shallow, deep, perched, water table, and/or artesian levels) from monitored observation wells, piezometers, test wells, drill holes, and pits, for the periods of record, and groundwater gradients from water level monitoring data.

9. Aquifer types and boundaries, including potential or known sources of groundwater recharge, and locations and flows from springs and seeps (groundwater discharge).

10. Groundwater chemistry and contamination, as needed or as appropriate, including water quality analyses, if appropriate.

11. Where there is evidence of a hydraulic connection between a nearby surface water body and the groundwater, continuous monitoring of both features for several hydrologic cycles is recommended.

21.6.4.5 Specialized Hydrogeologic Data

Specialized hydrogeologic data, if necessary, would include:

1. Vertical permeability of confining units (formerly referred to as aquitards or aquicludes (see the term “Confined aquifer” in Section 21.2.2,).

2. Gravity drainage rates for very fine materials.

3. Artesian pressures in underlying strata.

4. Long-term monitoring of water levels, artesian pressures, and gradients.

Field investigations and data collection protocols are discussed in detail in the *Groundwater Manual* (Bureau of Reclamation, 1995). General guidelines for design data collection can be found in the *Reclamation Manual, Design Data Collection Guidelines,* Chapter 4, “Specifications Designs,” Section 1, “Dams,” pp. 1-14 (Bureau of Reclamation, 2007b). Specific design standards can be found in Reclamation’s *Design Standards No. 1 - General Design Standards* (Bureau of Reclamation, 2009), and *Design Standards No. 13 - Embankment Dams* (Bureau of Reclamation, in revision).

21.6.5 Field Exploration Request

Each construction site is different with its own unique conditions, features, design requirements, and considerations. The WR&C system design should not only fit the existing site conditions, but it should also incorporate existing conditions to enhance the effectiveness of the system(s). The WR&C system design has the added requirement/constraint that it must be compatible with the excavation plans and construction access constraints.

The exploration program to acquire the needed design data is, of necessity, unique and site specific. As discussed previously, many of the geotechnical design data investigations fora project (i.e., an embankment dam modification project) can incorporate the collection of the design data needed for WR&C design. Therefore, it is important that the WR&C specialist be involved in the preparation of the FER and the design of the data acquisition program to ensure the necessary information to design an efficient and cost-effective WR&C system. Additionally, having the WR&C specialist involved in the exploration program significantly reduces the likelihood of duplicated effort, wasted resources and manpower, project delays, and missing and/or inappropriate data.

Groundwater Lowering in Construction (Cashman and Preene, 2001) and *Construction Dewatering and Groundwater Control* (Powers et al., 2007) both devote whole chapters to the layout and implementation of exploration/data collection programs, albeit in generalized terms. Not all of the considerations above or discussed by Cashman and Preene (2001) or Powers et al. (2007) may be applicable or necessary at a given embankment dam site. There may be unique or unusual field conditions in which it may be appropriate to seek the assistance of an outside dewatering consultant familiar with the area to help identify unique design data needs and specialized data collection requirements, and to design a WR&C system for a given project site.

21.6.6 Laboratory Testing

Laboratory testing consists of several types of tests using samples collected during geotechnical investigations and exploratory drilling. Geotechnical investigations and laboratory analysis can provide valuable information for designing WR&C systems; and in the absence of exploratory drilling and field testing, it may be the only available source to obtain reasonable estimates of aquifer parameters.

21.6.6.1 Gradation Analysis for Estimating *K*

The simplest laboratory test is the gradation analysis. This test is most often performed using samples obtained from test pit samples and exploratory drilling. The samples need to be completely dry, unconsolidated material needs to be broken up, and a sufficient amount of sample needs to be collected to perform a representative analysis.

It is recommended that several samples from each layer or interval be collected. The minimum amount of sample needed per gradation analysis depends on the maximum particle size of the material and range from 50 grams for a maximum particle size of a No. 40 sieve (0.017 inch) to 70 kilograms for a maximum particle size of 3 inches (ASTM, 2009). It is recommended that the amount of sample collected should be at least three times the amount needed per gradation analysis to allow for sample preparation, sample splitting, replicate analyses, and sample "spillage"[6].

The estimate of the hydraulic conductivity of the sample can be obtained either through a visual curve matching of the gradation curve or by computing ***K*** using one of a number of empirical formulae.

1. **Visual Curve Matching**. Estimated ***K*** is based on a gradation curve and by comparing it to figure 21.6.6.1-1. Gradation analyses can be significantly influenced by the field sampling technique and the selection of the material to be "graded"[7] Grab samples from drill cuttings can be a mixture of materials from several horizons in the borehole; if drilling fluids are used, then fines may be washed out or added to the sample in the case of using drilling muds. Core or driven samples are limited to the size of the core barrel opening. Materials larger than the barrel opening will block the barrel opening and prevent a representative sample from being obtained.

2. Very fine-grained sands and unconsolidated materials may fall out of the barrel while being retrieved, and only a portion of the sample is recovered (if at all). Even for a good sample, the way the material sample is extracted from the core barrel can influence the gradation results. Some questions to be considered are: Is the sample from one horizon? Is the sample a mixture of layers or horizons? Is the sample representative of the core or formation? Has the logging made an attempt to describe and sample the separate types of materials encountered? How often do the materials change, and can the material only be reasonably sampled and logged as a mixture (as in the case of thinly bedded lamina)?

3. For gradations that are more well-graded than those shown in figure 21.6.6.1-1, the finer end of the gradation curve should be used to estimate ***K***. Analysis of silty or clayey soils should be performed in accordance with Reclamation standards.

4. Visual curve matching assumes that the materials are homogeneous and isotropic, so a few nonrepresentative samples could significantly skew the estimates of ***K*** across the site. Therefore, it is recommended that multiple samples be obtained from each material type, from multiple locations within each material type, and from multiple depths within each material type.

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[6] Spillage refers to the loss of sample material due to normal laboratory procedures, such as material remaining in the sample bag, material stuck to the sample splitter, dust from the sample, and the inevitable loss of sample material when it is being transferred from one container to another.

[7] Graded refers to the determination of the range of particle sizes in a sample.

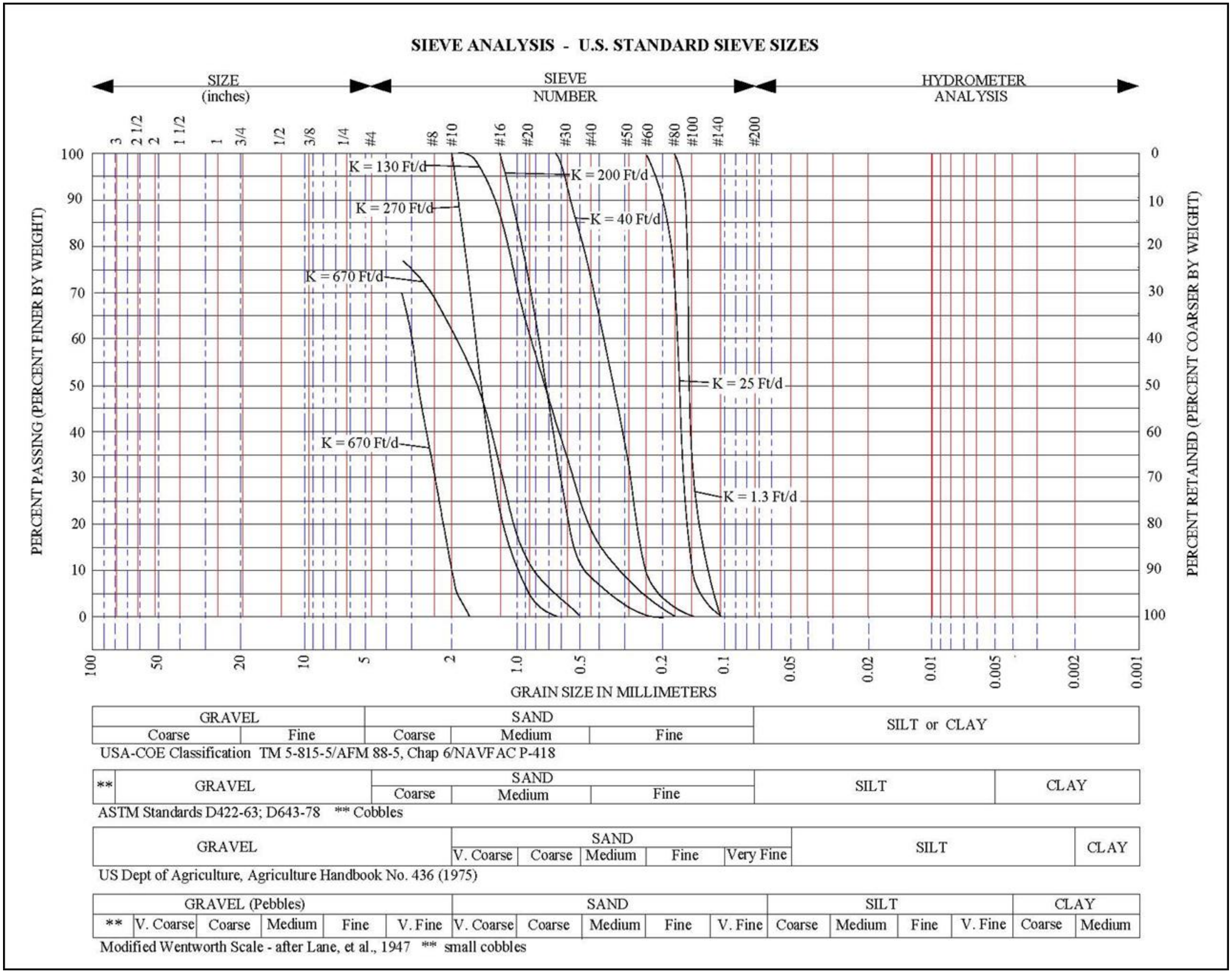

Figure 21.6.6.1-1. Relationships between hydraulic conductivity and grain sizes based on gradation curve shapes (adapted and modified from Bureau of Reclamation, 1995; USACE, 2004; AGI, 1982, Powers et al., 2007; and Sterrett, 2007).

5. **Empirical Formulae.** There are six empirical formulae in common usage that have been developed to estimate hydraulic conductivity based on the gradation analysis. All of them have the same limitations as described in subparagraph 1 above. The gradation analysis is used to obtain the effective grain size (or simply the material's effective size) and the Uniformity Coefficient (U) (or grain uniformity) of the material.

   These formulae are adaptations of the general equation (Garrick, 2011) developed by Vukovic and Soro (1992):

$$\boldsymbol{K} = \left(\frac{g}{\mathrm{v}}\right) * \mathrm{C} * f(\eta) * \boldsymbol{D}_{\mathrm{e}}^{2} \qquad \text{Eq. 1}$$

   Where:

$\boldsymbol{K}$ = Hydraulic conductivity (units of m/day unless otherwise noted)
g = Acceleration due to gravity (meters per second squared)
v = Kinematic viscosity of a fluid (determined by the ratio of dynamic viscosity to density of the fluid; in this case, the fluid is water) (meters squared per second)
C = Sorting coefficient – depends on the method used in the grain-size analysis (dimensionless)

$f(\eta)$ = Porosity function – depends on the method used in the grain-size analysis. Porosity (η) may be measured in the laboratory or derived from the empirical relationship:

$$\eta = 0.255(1+0.83^{Cu}) \qquad \text{Eq. 2}$$

$\boldsymbol{D}_{\mathrm{e}}$ = Effective grain diameter – depends on the method used in the grain-size analysis
Cu = Uniformity coefficient - $\boldsymbol{D}_{60}/\boldsymbol{D}_{10}$ (% passing)

The following formulae are not presented in their original forms as they first appeared in the literature; rather, they have been rewritten to use consistent symbols and nomenclature. Additionally, they are generally presented in order from most accurate or most widely used to least accurate or least widely used. The order of presentation is considered general because different authors rank the formulae differently, although the Slitcher and Reclamation methods consistently rank at the bottom, and the Kozeny-Carman, Hazen, Terzaghi, and Breyer formulae consistently rank in the top three.

When using any of the six formulae, it is important to note under what conditions the formulae were developed and not violate those assumptions. The six formulae (or seven because there are two versions of the Terzaghi formula) in common usage are:

a. **Kozeny-Carman.** Applicable for most soil textures, except soils with an effective grain size greater than 3 millimeters (mm) or for clayey soils. Input requirements are:

(1) Total porosity (η) as a fraction of 1.0.

(2) Effective diameter of $\boldsymbol{D}_{10}$ in mm.

$$\boldsymbol{K} = \left(\frac{g}{v}\right) * 8.3\text{x}10^{-03}\left[\frac{\eta 3}{(1-\eta)^2}\right] * \boldsymbol{D}_{10}^2 \qquad \text{Eq. 3}$$

b. **Hazen.** Applies to sands and gravels with an effective grain diameter of between 0.1 and 3.0 mm and a uniformity coefficient of $\boldsymbol{D}_{60}/\boldsymbol{D}_{10}$ less than 5. Required inputs are:

(1) $\boldsymbol{D}_{60}$ and $\boldsymbol{D}_{10}$ – particle diameters in mm where 60% and 10% of the materials are finer (i.e., percent passing, respectively).

(2) Water temperature in degrees Celsius (^{o}C) (used to determine v).

(3) Empirical coefficient – typical values are 0.4 to 0.8 for clayey and nonuniform sand, and 0.8 to 1.2 for clean and uniform sand (the more uniform the sand, the higher the coefficient).

The uniformity coefficient of $\boldsymbol{D}_{60}/\boldsymbol{D}_{10}$ (% passing) is calculated outside of the Hazen formula:

$$\boldsymbol{K} = \left(\frac{g}{v}\right) * 6.0\text{x}10^{-04} * [1 + 10(\eta - 0.26)] * \boldsymbol{D}_{10}^2 \qquad \text{Eq. 4}$$

c. **Terzaghi.** Applies mostly to coarse-grained sand and gravel. Input values are:

(1) Formation water temperature in ^{o}C (used to determine v).

(2) Total porosity (η) as a fraction of 1.0.

(3) Effective diameter of $\boldsymbol{D}_{10}$ in mm.

(4) Correction coefficient, $\beta_{T,}$ to account for smooth or angular sand grains.

$$\boldsymbol{K}\left(\frac{\text{cm}}{\text{s}}\right) = \left(\frac{g}{v}\right) * \beta_{\text{T}} * \left(\frac{\eta - 0.13}{\sqrt[3]{1-\eta}}\right)^2 * \boldsymbol{D}_{10}^2 \qquad \text{Eq. 5}$$

Where:

β_T = $10.7 \text{ x}10^{-03}$ for smooth sand grains
β_T = $6.1 \text{ x}10^{-03}$ for angular sand grains

d. **Breyer.** The Breyer formula was developed for heterogeneous soils with poorly sorted grains, effective grain size between 0.06 mm and 0.6 mm, and a uniformity coefficient between 1 and 20. Inputs to the Breyer formula are:

(1) Uniformity coefficient.

(2) Effective size of $\boldsymbol{D}_{10.}$

$$\boldsymbol{K} = \left(\frac{g}{v}\right) * 6 \text{ x}10^{-04} * \log\left(\frac{500}{C\text{u}}\right) * \boldsymbol{D}_{10}^2 \qquad \text{Eq. 6}$$

Where:

Cu = Uniformity coefficient – $\boldsymbol{D}_{60}/\boldsymbol{D}_{10}$ (% passing gradation)

e. **Slichter.** Applies to sands and gravels with an effective grain diameter between 0.01 and 5.0 mm and a uniformity coefficient of $\boldsymbol{D}_{60}/\boldsymbol{D}_{10}$ less than 5. Instead of an empirical coefficient, the Slichter formula uses a total sand porosity correction factor, as well as a water temperature correction factor. The required inputs are:

(1) $\boldsymbol{D}_{60}$ and $\boldsymbol{D}_{10}$ – Particle diameters in mm where 60% and 10% of the materials are finer (i.e., percent passing, respectively).

(2) Water temperature in $^{\circ}$C (used to determine v).

(3) Total sand porosity (η) as a fraction of 1.0.

(4) The uniformity coefficient of $\boldsymbol{D}_{60}/\boldsymbol{D}_{10}$ (% passing) is calculated outside of the Slichter formula.

Note that in the Slichter formula, the $\boldsymbol{D}_{60}$ and $\boldsymbol{D}_{10}$ values are for "percent passing," when used to calculate the uniformity coefficient; however, when input into the formula, the $\boldsymbol{D}_{10}$ value is for percent retained (90% passing).

$$\boldsymbol{K} = \left(\frac{g}{v}\right) * 0.01 * \eta^{3.287} * \boldsymbol{D}_{10}^2 \qquad \text{Eq. 7}$$

Assuming pure water at 4 ºC, and combining constants, the equation simplifies to:

$$\boldsymbol{K}\left(\frac{\mathrm{m}}{\mathrm{day}}\right) = 4960 * \eta^{3.287} * \boldsymbol{D}_{10}^{2} \qquad \text{Eq. 8}$$

f. **Reclamation.** Applies to medium-grained sand where the effective grain diameter in mm is $\boldsymbol{D}_{20}$, and the uniformity coefficient is less than 5. There is no correction for temperature, nor is there an empirical coefficient. The only input is the $\boldsymbol{D}_{20}$ particle size.

$$\boldsymbol{K} = \left(\frac{g}{v}\right) * 4.8 \times 10^{-04} * \boldsymbol{D}_{20}^{0.3} * \boldsymbol{D}_{20}^{2} \qquad \text{Eq. 9}$$

Assuming pure water at 4 $^{\circ}$C, and combining constants, the equation simplifies to:

$$\boldsymbol{K}\left(\frac{\mathrm{cm}}{\mathrm{sec}}\right) = .036 * \boldsymbol{D}_{20}^{2.3} \qquad \text{Eq. 10}$$

The Kozeny-Carman formula is reportedly the most widely used and accepted empirical equation (Garrick, 2011). However, other authors indicate that the Reclamation formula is widely used in the United States. The Reclamation formula, using only one parameter, is the least accurate method but uses a parameter that can be estimated in the field. The other formulae use parameter(s) that are not, or cannot be, easily estimated in the field, and the accuracy is generally considered to fall between the Kozeny-Carman and the Reclamation formulae.

Multiplying the value of $\boldsymbol{K}$ obtained from the Reclamation formula by 36 will result in a value similar to the Hazen, Kozeny-Carmin, and Breyer formulae. Multiplying the Reclamation $\boldsymbol{K}$ by 16 will result in a value similar to the Slitcher formula, while multiplying it by 240 will result in a value similar to the Terzaghi formula.

In addition to the above seven formulae, there have been other formulae developed for specific cases or in specific materials, such as the original Kozeny Formula, the Sauerbrei Formula, the Pavchich Formula, the Kruger Formula, the Boonstra and de Ridder Formula, the Zamarin Formula, and the Zunker Formula (Kasenow, 2002). These formulae are not discussed herein, but they generally require input consisting of coefficients for shape of the grains or input from tables derived from empirical data.

21.6.6.2 Permeameter Testing

Laboratory permeameter testing consists of two techniques: (1) falling head tests and (2) constant head tests (USACE, 2004; ASTM, 2007).

1. **Constant Head Permeameter**. In a constant head test (figure 21.6.6.2-1a), a soil sample or core sample of length *L* and cross-sectional area *A* is inserted tightly into a cylindrical tube and capped at both ends with porous plates at each end of the sample. A constant head differential, H, is set up across the sample and the flow, *Q*, is measured where *Q* (Volume V in time t) is the steady-state flow of water through the system.

2. **Falling Head Permeameter**. In a falling head test (figure 21.6.6.2-1b), the sample setup is the same as for the constant head permeameter test. The difference is that the head in a tube of known cross-sectional area is allowed to fall from h_o to h, and the time is recorded.

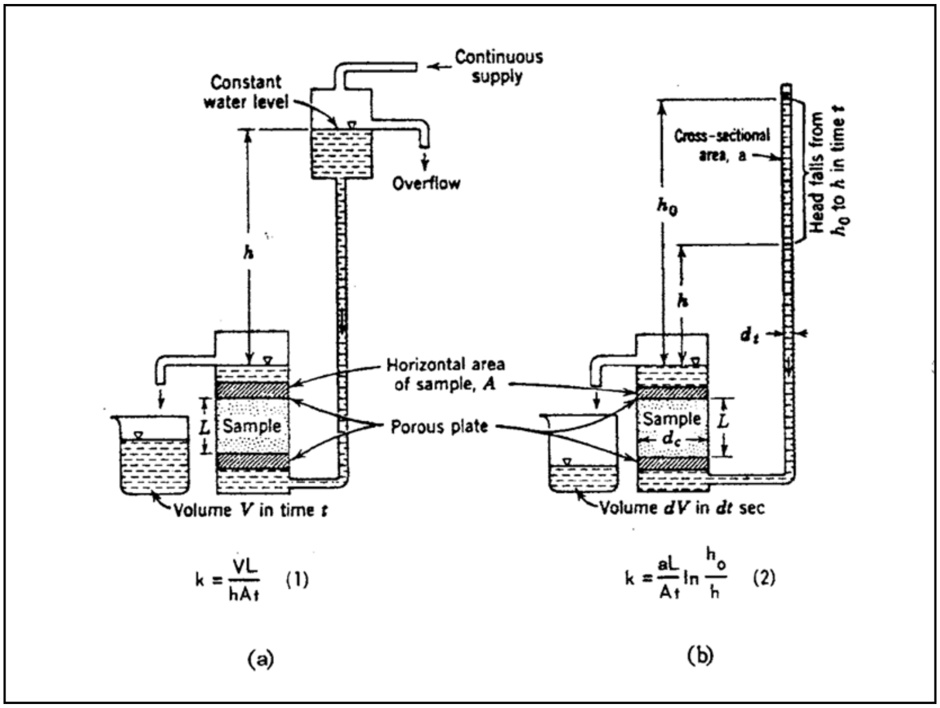

Figure 21.6.6.2-1. Permeameters: (a) constant head and (b) falling head (after USACE, 2004; ASTM, 2007).

In the first case, the constant head test, the known values are inserted into Darcy's law and solved for ***K***.

$$\boldsymbol{K} = \frac{\mathrm{QL}}{\mathrm{Ah}} \qquad \text{Eq. 11}$$

In the second case, the falling head test, the known values are inserted into a slightly modified version of Darcy's law and solved for K.

$$\boldsymbol{K} = \left[\frac{a\mathrm{L}}{At}\right] \ln\left(\frac{\mathrm{h_0}}{\mathrm{h_1}}\right) \qquad \text{Eq. 12}$$

Ideally, the tests should be run on an undisturbed sample of the material. However, the simple act of collecting the sample, usually in the form of a core sample, will cause a disturbance along the walls of the sample. Additionally, when testing a normal vertical core sample, the value of K being solved for is the vertical K, K_v. K_v is typically less than K_h, the horizontal conductivity, and can be one or more orders of magnitude smaller.

Highly disturbed samples, and reconstituted samples, can be tested, but the values for K are questionable and probably only useful for gross estimates of K.

Regardless, any sample tested in the lab will only provide conductivity values for just that sample and at the location and depth of that sample in the field. The sample may or may not be representative of the materials to be dewatered. A large number of samples are required to be tested at various depths, in different materials, and from multiple locations across the site to capture the variability of vertical and horizontal aquifer parameters of the site.

The small sample sizes used in permeameter tests cannot capture the large-scale characteristics in soils, and the resulting field conductivity values are likely to be greater than what is indicated by laboratory testing.

21.6.7 Field Testing

In addition to geotechnical investigations, the primary means of obtaining hydrogeologic field data is through borehole testing (geophysics and slug tests) and aquifer testing (also known as pump test, pumping test, and pump-out test). The parameters of most interest to the design of WR&C systems are hydraulic conductivity (K), storativity (S), and porosity (η).

Field testing is the only method that will determine in-situ hydraulic conductivity. Hydraulic conductivity can be determined in single wells where only the materials immediately adjacent to the well are evaluated and in multiple well tests where the materials between the wells are evaluated. The means of determining hydraulic conductivity (K), from least accurate to most accurate, are:

1. Visual classification of field samples.

2. Geophysical testing.

3. Single well testing (slug and bail tests).

4. Single pumping well tests (a single pumping well with no observation wells).
5. Multiple single well tests (a pumping well and multiple observation wells).

6. Multiple well tests (multiple pumping wells and observation wells).

Many Reclamation projects are in relatively narrow river valleys where boundary conditions, rather than transmissivity and storativity, may control the later stages of inflow to the WR&C system. Boundary conditions would typically include:

- Constant high heads in the strata of the dam foundation due to the reservoir levels
- Relatively impervious boundaries on the sides of the valley due to bedrock in the valley walls
- A constant recharge source from a stream/river flowing through or adjacent to the excavation site due to releases from the dam’s spillway and/or outlet works or diversion channels

In such conditions, conducting one or more tests involving simultaneous pumping of several closely spaced wells can be employed to obtain a clearer picture of interference and boundary effects.

Storativity can be calculated from the results of field aquifer tests, although it cannot be measured directly in the field. Porosity can only be accurately determined in the laboratory.

21.6.7.1 Estimating K from Visual Classification

Visual classification of field samples: estimated ***K*** based on a field classification of the aquifer material and comparing the material to figure 21.6.7.1-1 or 21.6.7.1-2. Note that, as indicated in figure 21.6.7.1-2, many materials have a wide range of ***K*** values. For unconsolidated materials, ***K*** is a function of the material’s physical properties such as gradation ranges, effective sizes, porosity, and uniformity coefficients. Results are dependent on the observer’s familiarity and experience with classifying field samples accurately.

In the absence of laboratory testing, an estimated value for ***K*** can be selected from one of the figures mentioned in the preceding paragraph or an “average” or “common”[8] value for specific types of materials as reported in the literature may be used. Many textbooks, as well as some Web sites, have a variety of tables of average or common aquifer parameters. Some of them have only a few materials and/or a few parameters, while others have more of either or both. Table 21.6.7.1-1 is a compilation of material types and aquifer properties from two software packages by Waterloo Hydrogeologic, Inc.[9] of Waterloo, Ontario, Canada.

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[8] Average or common values, as reported in the literature or shown on various graphs or other figures, are based either on the average of several measured values or commonly accepted ranges of values for particular material types.

[9] Waterloo Hydrogeologic, Inc., is now a subsidiary of Schlumberger Water Services.

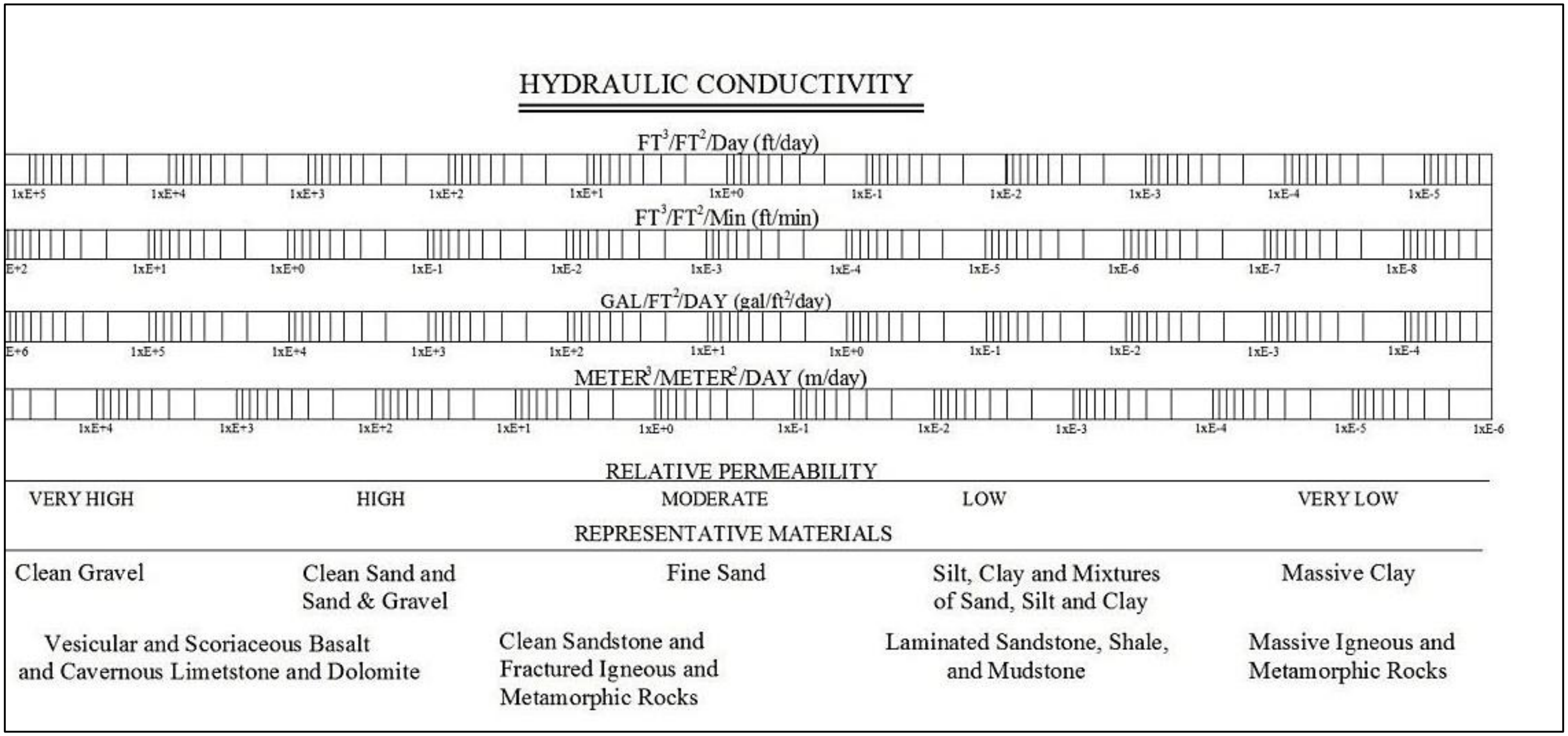


Figure 21.6.7.1-1. Comparison of hydraulic conductivities for generalized material classifications (modified from Bureau of Reclamation, 1995).

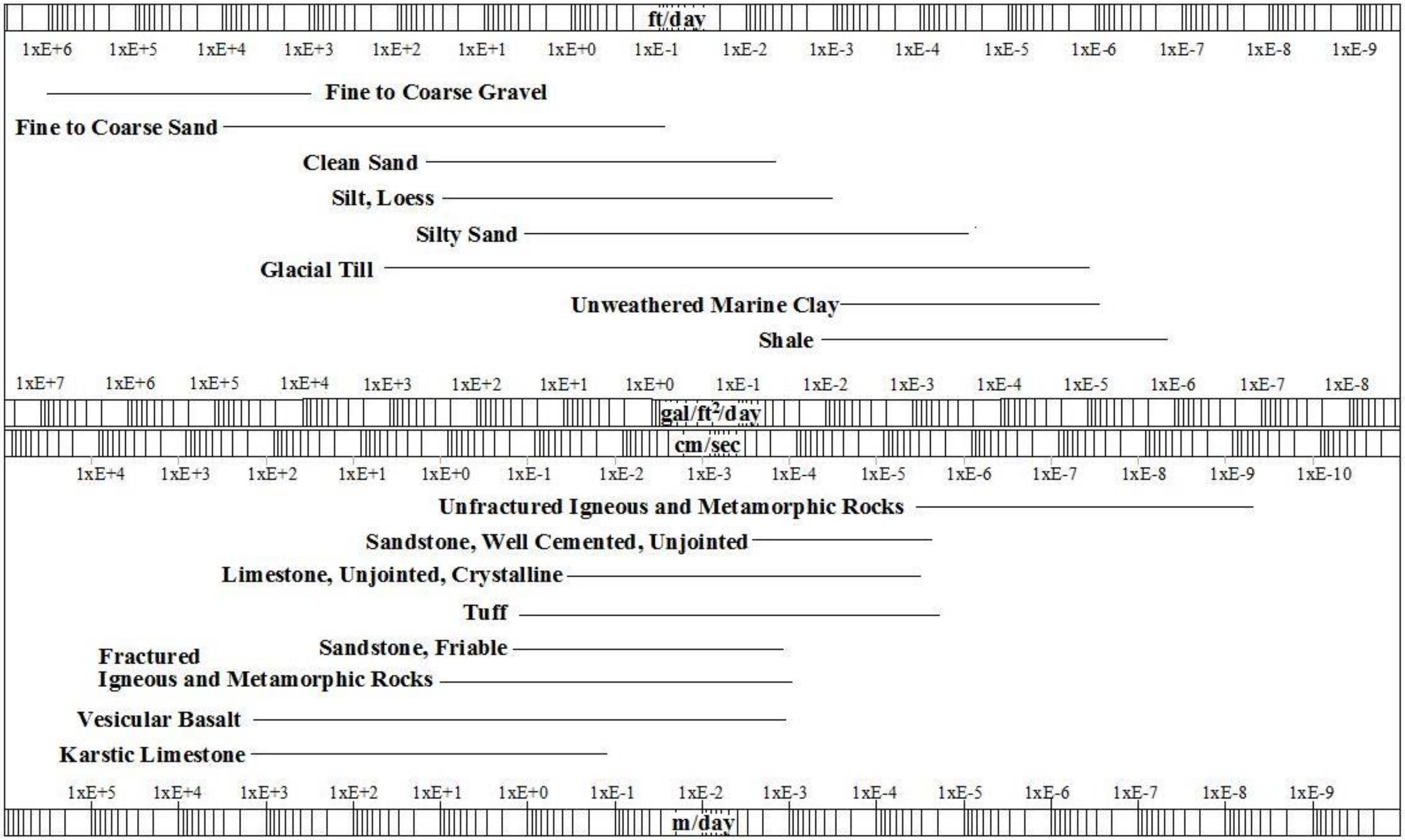


Figure 21.6.7.1-2. Graphical representation of hydraulic conductivity ranges of water for some commonly encountered materials and comparisons of those ranges between materials. The ranges shown for each material do not take into account corrections for material density, material porosity, formation temperature, or fluid viscosity (modified from Bureau of Reclamation, 1993 and 1995).

Table 21.6.7.1-1 Average and/or Representative Values for Hydraulic Conductivity, Specific Yield, Specific Storage, and Porosity for Some Common Materials (values are in SI units as reported in the data bases and have not been converted to English units).

Material	Hydraulic Conductivity (meters per second)		Specific Yield		Specific Storage (1/m)		Porosity	
	Low	High	Low	High	Low	High	Low	High
Alluvium	1.70E-05	3.10E-03					0.20	0.40
Alluvium, sand and gravel with clay lenses	0.001 *							
Anhydrite	4.00E-11	2.00E-08						
Basalt	2.00E-11	4.20E-07	0.02	0.10	5.00E-02	3.00E-01	0.04	0.18
Basalt, fractured	1.20E-06	5.00E+00	0.01		3.80E-06		0.05	0.50
Basalt, vesicular	5.00E-07	1.00E-02	0.04				0.50	
Basalt, weathered			0.07				0.34	
Basaltic lava and sediments	1.80E-03	1.80E-01					0.10	
Chalk	1.00E-04	1.10E-03					0.00	0.50
Chalk, fractured	2.20E-03							
Clay	1.00E-13	1.00E-08	0.00	0.18	1.00E-04	1.00E-02	0.20	0.70
Clay, unweathered marine	8.00E-13	2.00E-07						
Clayey sand	1.00E-08	1.00E-06						
Clayey silt	2.00E-08	3.00E-07			1.00E-04	5.00E-04		
Clayey slate	3.00E-06	5.30E-06						
Coal	8.10E-07	7.50E-06	0.01		6.00E-05			
Dolomite	1.00E-09	5.10E-04	0.01	0.15			0.00	0.20
Dolomite and limestone	2.20E-04	6.60E-04					0.04	0.08
Dolomite and limestone, fractured	7.00E-08	7.30E-03	0.02	0.05			0.06	0.60
Dolomite, fractured	7.80E-06	8.80E-04					0.01	0.20
Dolomite, weathered	2.00E-05							

Table 21.6.7.1-1 Average and/or Representative Values for Hydraulic Conductivity, Specific Yield, Specific Storage, and Porosity for Some Common Materials (values are in SI units as reported in the data bases and have not been converted to English units).

Material	Hydraulic Conductivity (meters per second)		Specific Yield		Specific Storage (1/m)		Porosity	
	Low	High	Low	High	Low	High	Low	High
Gabbro, weathered	5.50E-07	3.80E-06						
Glacial outwash	3.60E-05	3.30E-03	0.20	0.30			0.35	
Glacial till	8.00E-12	8.50E-06	0.03	0.18	2.00E-04	1.00E-03	0.30	0.35
Glacial till and fine sand	2.70E-05						0.00	0.01
Gneiss					6.90E-06	2.20E-05		
Gneiss, fractured	1.80E-06				7.60E-07	2.20E-06		
Granite	6.00E-12				1.60E-03		0.02	
Granite, fractured	3.00E-05	5.80E-05			1.70E-05	1.10E-04		
Granite, weathered	5.80E-06	1.60E-05	0.01					
Gravel	1.00E-04	3.00E+00	0.15	0.30	1.20E-05	6.90E-05	0.20	0.34
Gravel and cobbles	2.90E-03						0.22	
Gravel, coarse			0.12	0.26				
Gravel, fine			0.13	0.40				
Gravel, layered with silty sand	8.10E-05	6.60E-03						
Gravel, medium			0.13	0.44				
Gravelly clay	1.00E-10	1.00E-07						
Gravelly silt	1.00E-07	1.00E-06						
Igneous and metamorphic rocks, fractured	8.00E-09	3.00E-04	0.02	0.05	1.00E-07	2.00E-05	0.00	0.10
Igneous and metamorphic rocks, unfractured			0.00	0.03	1.00E-05	1.00E-04	0.00	0.05
Igneous and metamorphic rocks,			0.10	0.20			0.20	0.40

Table 21.6.7.1-1 Average and/or Representative Values for Hydraulic Conductivity, Specific Yield, Specific Storage, and Porosity for Some Common Materials (values are in SI units as reported in the data bases and have not been converted to English units).

Material	Hydraulic Conductivity (meters per second)		Specific Yield		Specific Storage (1/m)		Porosity	
	Low	High	Low	High	Low	High	Low	High
weathered								
Limestone	1.00E-09	1.00E-04	0.00	0.36			0.02	0.35
Limestone, fractured	9.00E-05	2.50E-02			1.00E-07		0.01	0.05
Limestone, karst	1.00E-06	2.40E+01					0.05	0.50
Loess	1.00E-09	2.00E-05	0.14	0.22			0.45	0.50
Salt	1.00E-12	1.00E-10						
Sand	1.00E-06	1.00E-02	0.02	0.30	5.00E-06	3.00E-04	0.25	0.50
Sand and gravel	1.00E-05	2.00E-03	0.20	0.35	1.00E-05	3.00E-05	0.15	0.35
Sand and gravel with clay lenses	9.00E-04						0.30	
Sand and gravel, glaciofluvial	5.90E-07	4.30E-02					0.07	0.40
Sand, clay and silt	5.00E-04						0.25	
Sand, coarse	9.00E-07	6.00E-03	0.18	0.43			0.12	0.35
Sand, eolian	2.30E-04		0.25	0.47			0.40	0.45
Sand, fine	2.00E-09	2.00E-04	0.01	0.46			0.45	
Sand, fluvial	7.00E-05	1.70E-02			1.70E-08	2.70E-05	0.40	0.45
Sand, glaciofluvial	1.70E-08	7.60E-05					0.30	0.40
Sand, gravel and silt	1.30E-03						0.25	0.40
Sand, medium	9.00E-07	5.00E-04	0.15	0.46			0.25	0.40
Sand, very fine	1.50E-04						0.50	
Sandstone	3.00E-10	1.00E-04	0.01	0.25			0.00	0.30
Sandstone with sand, silt and clay	2.90E-10						0.23	

Table 21.6.7.1-1 Average and/or Representative Values for Hydraulic Conductivity, Specific Yield, Specific Storage, and Porosity for Some Common Materials (values are in SI units as reported in the data bases and have not been converted to English units).

Material	Hydraulic Conductivity (meters per second)		Specific Yield		Specific Storage (1/m)		Porosity	
	Low	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Sandstone, fine	2.30E-06		0.02	0.40				
Sandstone, medium			0.21	0.41				
Sandy clay			0.03	0.12				
Sandy silt	2.00E-09	1.00E-06						
Schist			0.02	0.03				
Schist and gneiss, fractured	3.60E-07							
Shale	1.00E-13	2.00E-09	0.01	0.05			0.00	0.10
Shale, weathered	2.00E-06	3.00E+06			6.00E-05			
Silt	1.00E-10	2.00E-05	0.01	0.39			0.35	0.50
Siltstone	1.00E-11	1.40E-08	0.01	0.33			0.05	0.20
Silty sand	1.00E-07	1.00E-03						
Tuff	1.70E-06	2.30E-06	0.02	0.47				

* Merged cells with only one value indicate that only an average or a single value was reported (after Schlumberger Water Services, Enviro-Base Pro 1.0®, 2003 and EnviroBrower Pro 1.0®, 2007). Blank cells indicate that no values were contained in the data bases for those parameters for the indicated material type. References for the various materials tested and the values obtained are listed in the Enviro-Base Pro 1.0 and EnviroBrowser Pro 1.0 data tables.

Table 21.6.7-1-1 presents average, representative aquifer property values (in SI units) for a number of different materials. Values were obtained, in most cases, by averaging numerous laboratory analyses and/or field tests. In some cases, only one value is reported for a particular material, in which case the cells for the "Low" and the "High" columns are merged, and the one value is shown.

When site-specific data is unavailable, the values in table 21.6.7.1-1 may be used for estimating purposes in the initial phases of design – such as appraisal level or 30% design level estimates. Site-specific data is required before bringing the designs to the 60% design stage. In the absence of site-specific design data, the designs must be, of necessity, ultraconservative. When possible, a good practice is to pick high and low values for given strata to be dewatered and base initial designs on a range of potential values.

21.6.7.2 Geophysical Testing

Geophysical testing for dewatering projects is conducted in conjunction with physical testing methods (exploratory drilling, aquifer testing, etc.). The primary purposes of geophysical testing are to determine hydraulic conductivity of the materials and to determine the layering and extents of the subsurface materials. Geophysical testing methods only indirectly measure aquifer properties and must be correlated with physical testing methods, both in situ and in a laboratory setting. Geophysical survey results are used to improve WR&C system designs, including the locations, depths, and spacing of dewatering wells. This is due to the ability of geophysical surveys to provide extensive lateral and depth coverage along profile lines, rather than point location information as is typically derived from drilling data and geotechnical investigations. Geophysical survey data and drill data in combination can develop a more complete site characterization assessment than is possible with drill data alone. Geophysical methods are broken down into two primary categories: (1) surface geophysical methods and (2) borehole geophysical methods (see table 21.6.7.2-1).

Appendix A presents a more detailed discussion of geophysical methods and their application to obtaining aquifer parameters.

Table 21.6.7.2-1. Examples of Geologic/Hydrologic Targets and Applicable Geophysical Methods (modified from Bureau of Reclamation, 1995)

Geologic/Hydrologic Target	Geophysical methods	
	Surface Methods	**Borehole Methods**
Bedrock configuration	Seismic refraction or reflection, electrical resistivity, EM[1], magnetic[LF], gravity[LF], GPR[LF 2]	Not applicable
Stratigraphy	Seismic refraction or reflection, electrical resistivity, EM	Sonic, electrical, or radiation logging; natural gamma, SP
Regional fault patterns	Gravity, magnetic	Not applicable
Local fracture zones/faults	Seismic reflection, electrical resistivity, EM, SP[3]	Sonic logging, borehole imaging, seismic tomography
Seepage/groundwater flow	SP	Temperature logging, flowmeters
Top of water table	Seismic refraction or reflection, electrical resistivity, EM	Not applicable
Porosity of geologic Materials	Not applicable	Sonic, electrical, or radiation logging
Density of geologic materials	Gravity	Radiation logging
Clay content, mapping aquifers, and aquicludes	Electrical resistivity, EM	Electrical, natural gamma, or radiation logging
Relative salinity of groundwater	Electrical resistivity, EM	Electrical logging

[1] EM = electromagnetic.
[2] GPR = ground penetrating radar.
[3] SP = Self-potential.
[LF] Less frequently used in this application.

21.6.7.3 Well Testing

1. **Single Well Testing (slug or bail test)**. There are two general configurations for single wells: one configuration in which the open end of the well is only open over a very short interval (such as in a single layer), and the other configuration in which the entire length or a significant portion of the length, of the well is open. In both cases, the test is initiated by inducing a near instantaneous change in the static water level of the well by removing a known volume of water (bail test) or adding a known volume of water (slug test).

The same effect can be achieved by rapidly inserting or extracting a solid cylinder of known volume (Cunningham et al., 2011). Three test configurations are possible, depending on the location of the water table or impervious boundary relative to the water level in the well (figure 21.6.7.3-1a) and are referred to as Condition I, II, and III, respectively.

Slug test results can be quickly estimated in the field where the water table or an impermeable barrier is below the test interval by using nomographs for Condition I or II, as appropriate (figures 21.6.7.3-1b and 1c, respectively). Alternatively, ***K*** can be calculated using the appropriate equation (Eq. 19 or Eq. 20, respectively) below and shown on the nomographs (figures 21.6.7.3-1b or 1c, respectively).

When the water table is above the test interval, known as Condition III (figure 21.6.7.3-1a), ***K*** can be calculated using the appropriate equation (Eq. 21) shown below (U.S. Environmental Protection Agency [EPA], 1994).

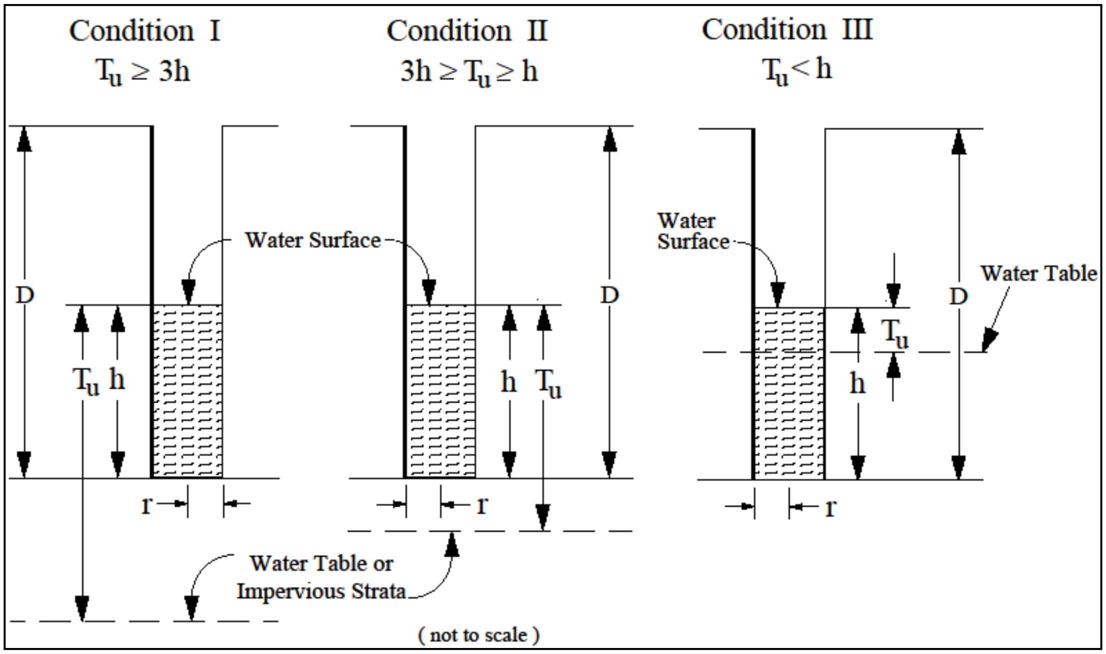
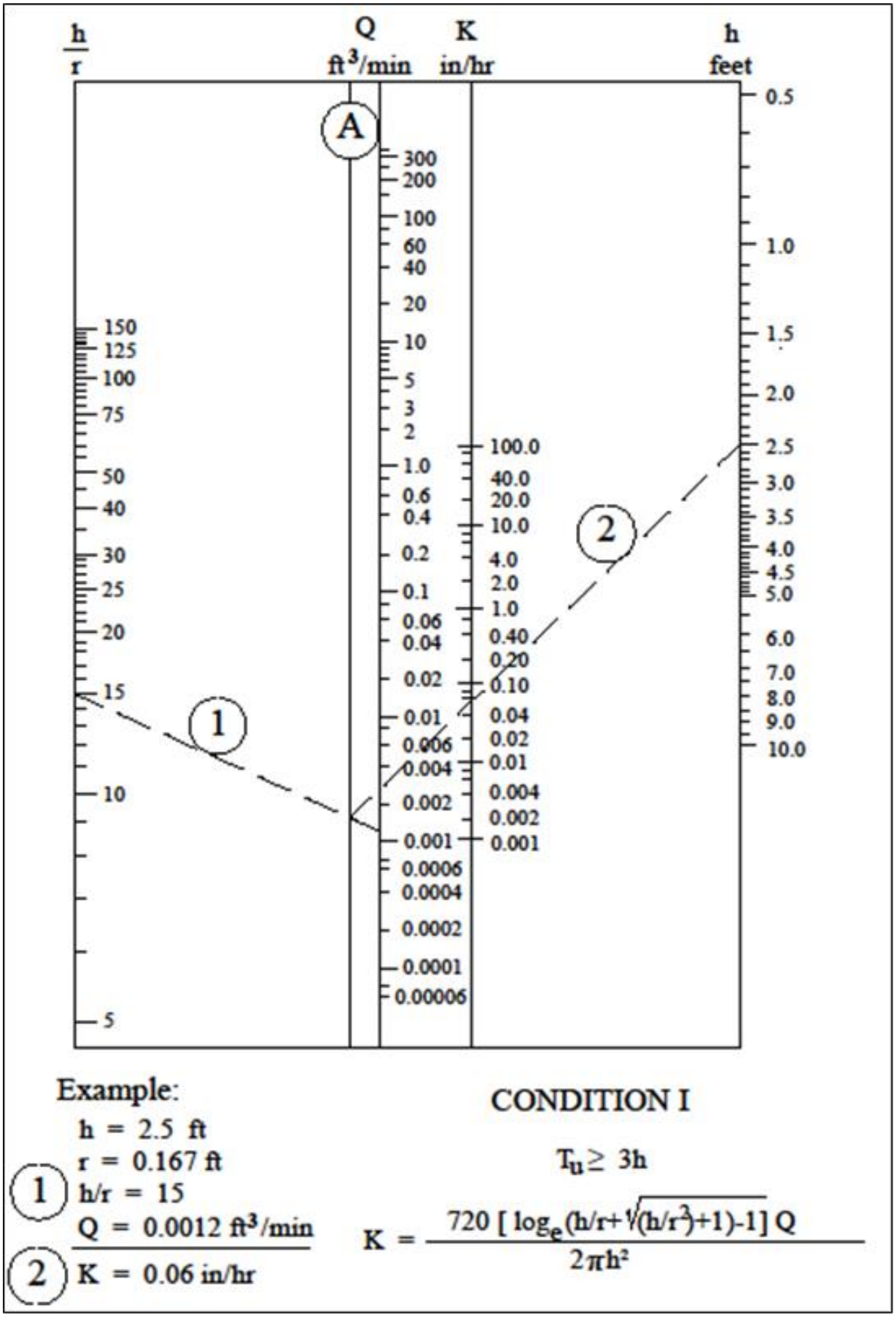


Figure 21.6.7.3-1a. Condition I, Condition II, and Condition III test configurations (modified from Reclamation, 1993; Reclamation 1995).



$$K = \frac{720\left[\log_e\left(h/r+\sqrt{(h/r)^2+1}\right)-1\right]Q}{2\pi h^2}$$

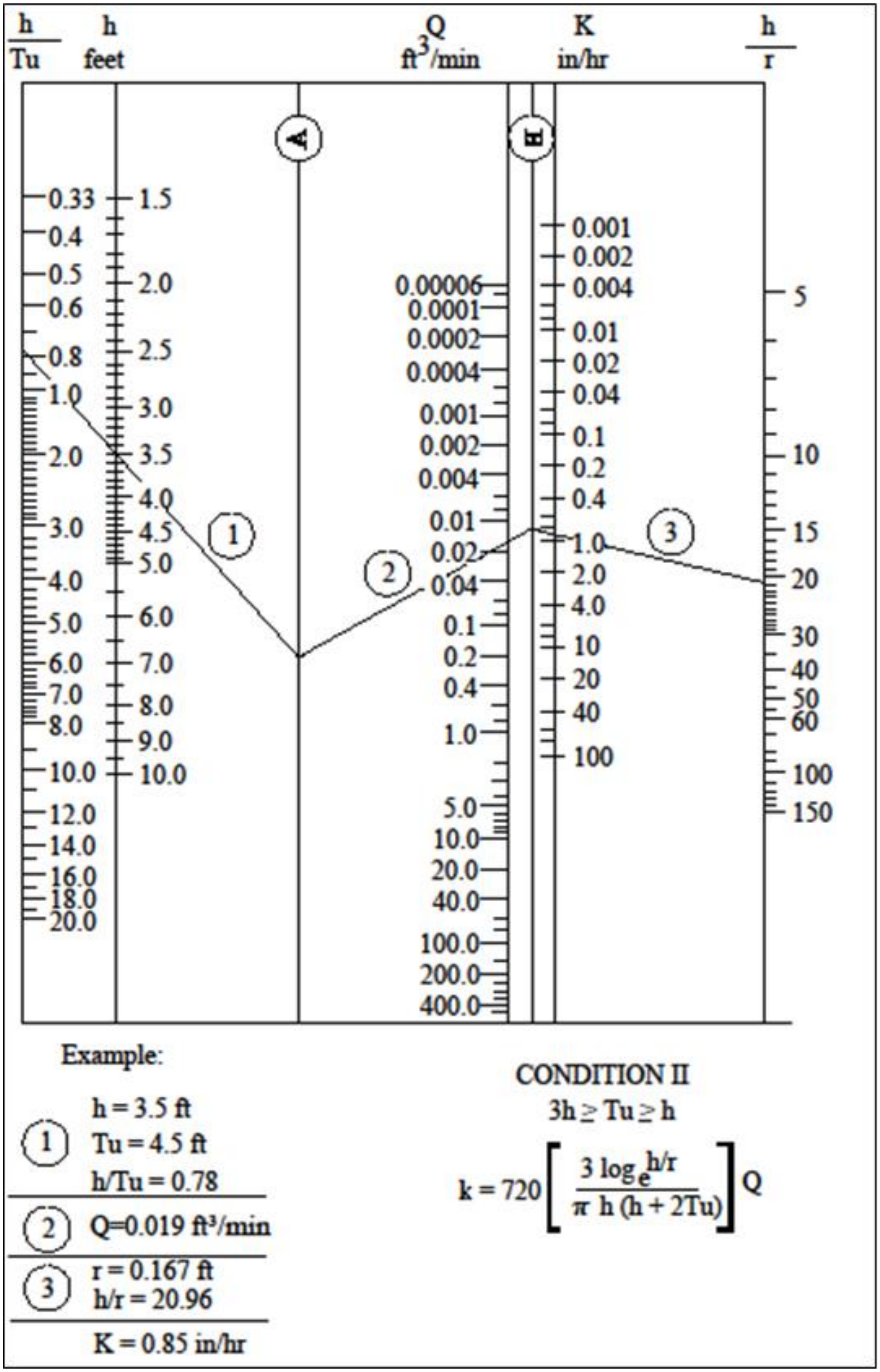
Figure 21.6.7.3-1b. Condition I nomograph for determining hydraulic conductivity from shallow well pump-in test data (modified from Reclamation, 1993 and Reclamation, 1995).

Condition I nomograph is used as follows (refer to figure 21.6.7.3-1a):

h = Depth of water maintained above bottom of hole
Tu = Depth of water table or impervious strata from surface of water maintained
r = Radius of the well
Q = Constant rate of flow into the well

1. Calculate h/r; draw a line between h/r and Q on the appropriate axes.
2. Draw a line between the intercept of line 1 with axis A and the value of h on the far right vertical axis.

The value of ***K*** is the point on the ***K*** axis where line 2 intersects the ***K*** axis.



$$k = 720\left[\frac{3\log_e h/r}{\pi\, h\,(h + 2Tu)}\right]Q$$

Figure 21.6.7.3-1c. Condition II nomograph for determining hydraulic conductivity from shallow well pump-in test data (modified from Reclamation, 1993 and Reclamation, 1995).

Condition II nomograph is used as follows (refer to figure 21.6.7.3-1a):

h = Depth of water maintained above bottom of hole
Tu = Depth of water table or impervious strata from surface of water maintained
r = Radius of the well
Q = Constant rate of flow into the well

1. Calculate h/Tu; draw a line from h/Tu through h to intersect vertical axis A.
2. Draw a line from the intersection of line 1 and axis A through Q and intersect vertical axis B.
3. Calculate h/r; draw a line between the intercept of line 2 with axis B and the value of h/r on the far right vertical axis.

The three slug test equations for Conditions I, II, and III, shown in figure 21.6.7.3-1a, are:

Condition I: when $Tu \geq 3h$

$$\boldsymbol{K} = \frac{720\left[\log_e\left(\left(\frac{h}{r}\right)+\sqrt{\left(\left(\frac{h}{r}\right)^2+1\right)}\right)-1\right]Q}{2\pi h^2} \qquad \text{Eq. 13}$$

Where:

$\boldsymbol{K}$ = Hydraulic conductivity (feet per second [ft/s])
r = Casing radius (ft)
h = Initial static water level
Tu = Distance between h and the water table or impervious boundary

Condition II: when $3h \geq Tu \geq h$

$$\boldsymbol{K} = 720\left[\frac{3\log_e\frac{h}{r}}{\pi h(h+2Tu)}\right]Q \qquad \text{Eq. 14}$$

Condition III: when $Tu < h$

$$\boldsymbol{K} = \frac{r^2 \ln\left(\frac{L}{R}\right)}{2\,L\,T_0} \qquad \text{Eq. 15}$$

Where:

L = Length of screen or open borehole (ft)
R = Radius of filter pack or borehole (ft)
T_0 = Value of t versus $(h-h_t)/Tu$ on semi-logarithmic plot where $(h-h_t)/Tu = 0.37$
h_0 = Water level at t = 0
h_t = Water level at t > 0

For $\left(\frac{L}{R}\right) > 8$ and static water level is above the top of the screen or open borehole,

$\boldsymbol{K}$ = Hydraulic conductivity (ft/s)
r = Casing radius (ft)
L = Length of open screen or borehole (ft)
R = Radius of filter pack or borehole (ft)

T_0 = Value of t on semi-logarithmic plot versus (H-h)/Tu where (H-h)/Tu = 0.37
H = Initial static water level
H_0 = Water level at t = 0
H = Water level at t > 0

Prior to initiation of the test, the static water level is recorded. At the initiation of the test, the instantaneous change in water level in the well is recorded. After the initiation of the test, the time it takes the well to return to pretesting static water level is recorded. Remaining head or remaining drawdowns should be measured at regular intervals throughout the test, along with the time of the measurement. See U.S Geological Survey (2011f) for a discussion of the procedures for conducting an instantaneous slug test using a mechanical slug and a pressure transducer.

The biggest limitation of the single well test is that only the materials immediately adjacent to the well and within the zone of influence of the water mound (slug test) or drawdown cone (bail test) are being tested. Other limitations include:

- The change in the static water level is assumed to be instantaneous.

- The amount of water that can be withdrawn or added in a very short time period is limited so the amount of initial head change in the piezometer is limited.

- The wells are generally small inside diameter wells, so the amount of downhole space available for the extraction or addition of water and for a water level measuring device is limited.

- Large diameter wells require significant amounts of water to be added or extracted to induce enough of a head change to obtain good test results. The U.S. Geological Survey (USGS) (2011f) suggests that 0.5 ft to 3.0 ft of head change is sufficient, depending on the diameter of the well – such that larger diameter wells require a greater amount of head change. Although there is no hard and fast rule as to how much head change is needed, most reference books, text books, and published articles that address this topic seem to agree that a head change of 2-1/2 to 3 times the diameter of the well will generally yield reliable results.

2. **Single Pumping Well Tests**. Single pumping well tests generally consist of one pumping (extraction) well and up to eight observation wells laid out in a pattern around the pumping well (also called the test well) at various distances and directions from the pumping well. These tests consist of recording the pumping rate(s) and water levels in the pumping well and observation wells over the entire duration of the test (commonly referred to as aquifer test, pump-out test, pumping test, or pump test). Additionally, water levels are

recorded in all wells as water levels return to prepumping levels (commonly referred to as the recovery period or recovery phase of the test).

These tests do not specifically test the materials immediately adjacent to the wells; rather, they test the aquifer system itself, or at least the part of the aquifer between the test well and the observation wells. This test provides results for how the aquifer system as a whole will respond to the dewatering activities and is a good method to use for the design and capacity of the dewatering system.

The observation wells are typically arranged in perpendicular lines of two to four wells per line centered on the pumping well (i.e., in the shape of a capital L with the pumping well at the vertex of the L). Where possible, the arms of the L are arranged such that one arm is parallel to the main groundwater gradient. The spacing between observation wells depends on the anticipated radius of influence of the pumping well, where the closest observation well is about 10 feet from the pumping well and the furthest well is near the anticipated radius of influence.

Two types of single pumping well tests are typically performed: (1) a step test and (2) a constant rate test. The step test consists of three to four steps of equal duration and of increasing yields starting at about 25% of the anticipated well yield and ending at about 110% of the anticipated yield. The yield for each step is maintained until the drawdown is constant. The main purpose of the step test is to determine the maximum sustainable yield that will be used in the constant rate test.

A typical constant-rate test is run at a constant yield over a 3- to 5-day period with a 2- to 3-day recovery period. The goal is to continue the pumping phase until the rate of change in the drawdown is zero in every well. Theoretically, the radius of influence never reaches equilibrium, and the drawdown continues to increase. However, the rate of change in the drawdown becomes increasingly smaller as the drawdown cone expands. Therefore, in practical terms, the rate of drawdown should be less than 0.01 foot per hour over a minimum of 4 consecutive hours – when the rate of change in drawdown in a well reaches this condition the drawdown in that well is said to have "stabilized"[10]. The recovery phase continues until the water levels in all wells have recovered to pretesting static water levels. In practical terms, because the water levels almost never recover to exactly the pretesting static levels, recovery is considered complete when water levels have recovered to within 95% of the pretesting levels and the

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[10] Theoretically, the drawdown in a pumping well will continue to increase as long as the pump is operating. However, after a certain amount of pumping, the rate of change in the drawdown will approach an extremely small value (e.g., hundredths of a foot per day). When the rate of change is within the measurement error of the measuring devices, then the drawdown is said to have 'stabilized'.

rate of change in water levels is less than 0.01 foot per hour over a period of 4 consecutive hours.

Both the early-time drawdowns and early-time recovery levels are critical values, so it is important to capture as many of the early-time values as possible. With automated data loggers, the frequency of readings is only limited by the delay in the sensors (e.g., pressure transducers). The delay is the amount of time it takes the sensor to warm up and obtain a measurement. In modern transducers, the delay is on the order of 5 to 10 milliseconds. With manual recorders (i.e., a person taking a measurement with an electronic water level indicator, a steel tape, or other such method), it usually takes two persons per well to obtain reliable readings; obtaining a reading every 15 seconds is usually considered fast. It is worth noting that even though automated data loggers can obtain upwards of 10 to 20 readings per second per well, such a frequency will produce thousands of readings per minute, and this is definitely a case where more is not better. Most data loggers are capable of obtaining readings on a log scale starting at one reading per second (per well) and decreasing to a user defined frequency at which the data logger shifts to a linear scale. In the absence of a built-in log scale, the user can usually program in a semi-log type of frequency. There are many different semi-log scales recommended, and each manufacturer of pressure transducers has a recommended semi-log scale based on the transducer's capabilities.

After the first 10 minutes of readings, the frequency of readings can gradually be decreased until the frequency reaches around 1 reading every 15 minutes. For extremely long tests, or for long-term observation, the frequency of readings may be one per hour or even down to one per day.

Most automatic data recorders and stand-alone pressure transducers have a built-in default semi-log scale. Whether the default semi-log scale can be modified or not depends on the specific model of data logger or pressure transducer used. In the absence of a manufacturer's recommended or default scale, one possible semi-log scale that will obtain reliable and useful readings in most cases is shown in table 21.6.7.3-1.

The time-distance-yield-drawdown data from the pumping and recovery phases of both the step test and the constant-rate test are analyzed using several methods as described in any number of reference books and text books, such as Freeze and Cherry (1979), Fetter (1980), and Sterrett (2007).

Constant rate tests are generally better for analyzing site-wide conditions, whereas step tests are better for analyzing localized conditions where highly nonheterogeneous materials are present.

Several proprietary computer programs exist that will not only perform the analyses but also import the data logger data files directly.

Table 21.6.7.3-1. Table of Semi-Log Water Level Reading Frequency

No. of Readings	From t =	To t =	Frequency
10	0 seconds	10 seconds	1 per second
10	10 seconds	30 seconds	1 per 2 seconds
18	30 seconds	120 seconds	1 per 5 seconds
60	2 minutes	12 minutes	1 per 10 seconds
60	12 minutes	42 minutes	1 per 30 seconds
60	42 minutes	102 minutes	1 per minute
60	102 minutes	402 minutes	1 per 5 minutes
60	402 minutes	1,002 minutes	1 per 10 minutes
4 per hour	1002 minutes	End of pumping	1 per 15 minutes

As in the single well tests,, single well aquifer tests also have limitations, including:

- Static water levels are never truly static; they are constantly changing due to barometric pressure changes.

- Drawdown in the pumping well is typically not representative of the drawdown in the aquifer immediately adjacent to the well due to the influence of the well's efficiency.

- The aquifer's ability to recover may be limited because of the amount of water extracted from the aquifer during the testing; the smaller the aquifer extent, the more significant is the influence of the amount of water produced during the testing.

- In aquifers with lower ***K*** values, it may take days for the aquifer to recover the last 5% of pretesting water levels due to the very small gradients involved.

3. **Multiple Single Well Tests.** Given the usual location of embankment dams in a stream or river valley or over a broad flood plain, it is expected that subsurface hydrologic conditions will vary considerably across the site and that the embankment materials will be quite uniform and represent a unique boundary condition in the local groundwater regime. Thus, it is highly recommended that multiple single pumping well tests be conducted across the site, particularly within the anticipated footprint of the planned excavation.

   Known areas of significantly different materials such as fill materials (either compacted or loose), undisturbed stream deposits and over-bank deposits, reworked areas, etc., should each be tested, and their extents should be determined as well as possible. The materials within or near known or suspected sources of recharge to the subsurface strata should also be evaluated to determine quantities and travel paths of recharge waters.

4. **Multiple Well Tests.** Multiple well tests generally consist of at least two pumping (extraction) wells and up to eight observation wells (piezometers) per pumping well. These tests involve conducting a single pumping well test on each pumping well and allowing the aquifer to recover to pretesting water levels between tests. Once all of the single pumping well tests are completed, all of the wells are tested, either in parallel or in series. When testing in parallel, all the pumping wells are turned on simultaneously, and the pumping phase continues until drawdowns in all the pumping and observation wells have stabilized. When testing in series, one well is turned on, and when the drawdowns in that well and its associated observation wells have stabilized, the next pumping well in the series is turned on. Thus, pumping wells are turned on in sequence until all pumping wells are running simultaneously. When drawdowns in all wells have stabilized, the pumping wells can either be turned off simultaneously or in series.

   In lieu of a multiple well test, current computer (numerical) groundwater models, such as MODFLOW, FEFLOW[11], and others, can be used to simulate multiple well tests. It cannot be overemphasized that computer models are only simulations based on the data input into the models. If inaccurate or wrong data are input, the computer simulation will run identically to the way it would run if accurate or correct data were input, unless the numerical algorithms "crash."[12] This is just one of the many aspects where the experience of the hydrogeologist and/or WR&C specialist plays a critical role in the evaluation of existing conditions and in the design of an efficient and effective WR&C system.

   This type of test indicates how the aquifer system, as a whole, might respond to the dewatering activities, and it is a good method to use for the design and capacity of the WR&C system. Although extensive multiple well testing is seldom ever done, a simplified version with two or three pumping wells will provide valuable data for calibration of a numerical groundwater model. As discussed later, the use of numerical models is a valuable tool for designing and testing WR&C designs, and calibration of the model is critical to the accuracy of any model simulation.

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[11] MODFLOW and FEFLOW are public domain, 3D groundwater model codes developed and maintained by the USGS. MODFLOW stands for MODular 3D finite difference FLOW model; FEFLOW stands for Finite Element 3D FLOW model.

[12] A computer simulation will "crash" when the model code encounters any of a number of conditions in the simulation, such as division by zero, the computations get into an infinite loop, or an iterative computation fails to converge on a solution which results in the simulation terminating without reaching a solution.

Considerations that should be taken into account when selecting a location or locations for slug and/or aquifer testing are:

- Existing data on subsurface materials and their extents
    - Drill logs from existing wells, piezometers, etc.
    - Geotechnical explorations such as test pits, SPT, Cone Penetrometer Test (CPT), etc.
    - Geologic cross sections
    - Previous construction reports

- Water level data from:
    - Existing wells and/or piezometers
    - Stream/river gage stations
    - Reservoir levels
    - Reservoir operations – timing and flow rates of releases
    - Correlation between subsurface water levels, reservoir levels, stream/river stage, and reservoir releases

- Previous construction WR&C methods and records, including previous aquifer test results

- Ongoing activities that might influence the location of test wells

- Location and size of planned excavation

- The number of each type of test that can be performed, taking into account access, equipment availability, timing, and costs

For example: At a recent dam modification site, one aquifer test was funded. There were three existing wells near the right side of the toe of the dam where the dam tender's house was located, along with several old piezometers along the toe. Logs existed for the three wells, and several of the piezometers were accessible. The dam tender's house and the wells were in the footprint of the planned excavation and, thus, were going to be removed.

Water level data from the piezometers and wells were sparse and old. Reservoir levels and operational data were up to date, but the nearest stream gage was well downstream of the construction area. WR&C was required during the original construction, but the quantities of water removed, the pump sizes, or the length of operation were not recorded.

Thus, to maximize the amount of data obtained, the aquifer test was set up to utilize the three existing wells and several of the piezometers as observation wells.

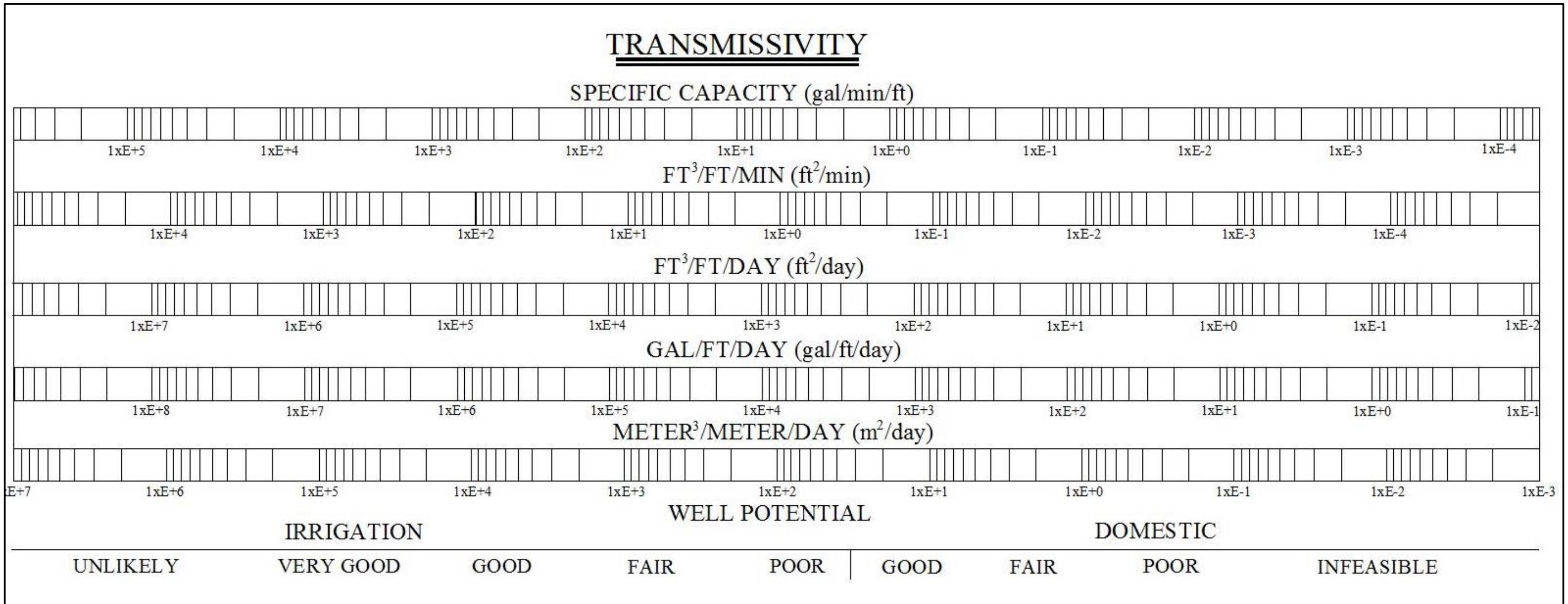
This example illustrates the value of aquifer tests for designing WR&C systems. Specifically designed aquifer tests are key to successful WR&C system designs. However, in the absence of specific aquifer testing, any data obtained from tests using existing wells or from other investigations is of value.

Some aquifer test analyses calculate the transmissivity of an aquifer instead of the conductivity, especially in confined aquifers. Transmissivity ($\boldsymbol{T}$) is related to conductivity by:

$$\boldsymbol{T} = \boldsymbol{K} * b \qquad \text{Eq. 16}$$

where 'b' is the saturated thickness of the aquifer. In a confined aquifer, $\boldsymbol{T}$ would be a constant; however, in an unconfined aquifer where the saturated thickness changes with changes in the water levels, $\boldsymbol{T}$ would be variable. Transmissivity will also have a wide range of values, depending on the material type (figure 21.6.7.3-2). Since $\boldsymbol{T}$ is also a function of saturated thickness, estimating an average value of $\boldsymbol{T}$ without knowing the saturated thickness is less certain than estimating an average value of $\boldsymbol{K}$ based on material types or characteristics.

In highly transmissive materials, the cone of depression will be shallow but very wide; while in low transmissive materials (all other factors being equal), the cone of depression will be narrow but deep.



Notes: Transmissivity (T) = K x M where K = Hydraulic Conductivity and M = Saturated thickness of the aquifer.
Specific capacity values based on pumping period of approximately 8-hours, but are otherwise generalized.

Figure 21.6.7-3-2. Comparison of transmissivities for generalized material classifications (modified from Bureau of Reclamation, 1993 and 1995).

21.6.8 Critical Design Parameter Analysis

General categories of critical design parameters were introduced in section 21.6.3, and specific types of data that should be collected, as appropriate, were listed in section 21.6.4. Each site and each construction activity will combine to create a unique set of critical design parameters which may or may not be readily apparent. What may at first appear to be a minor or insignificant parameter could turn out to be the key to whether one or more of the other parameters are critical or not.

> *For example: At the same dam site as discussed above in the previous section, the dewatering system should have only required nine extraction wells along with nine observation wells. After the wells were installed and operational, the yields varied from 5 to 10 gpm to around 300 gpm. After about 2 weeks of pumping, the water levels had stabilized considerably above the anticipated levels. Additional wells were installed where the water levels were remaining high; however, for each new well brought on-line, the yields in nearby wells would drop by a corresponding amount such that the cumulative yield from all the wells remained essentially the same. This went on until 36 pumping wells had been installed. The last two wells to be installed penetrated a highly productive sandy layer, and once those two wells came on-line, the water levels over the entire site began to rapidly drop.*
>
> *This high productivity zone turned out to be supplying nearly all the recharge to the site. This zone was exposed in the right abutment further upstream of the dam, and it was known to the original construction team, but as it passed under the dam and below the dam's cutoff wall, it was not deemed important and was not shown on any of the construction drawings or reports. Had it been shown, it could have been specifically targeted with one of the first wells to be installed, and considerable time and money could have been saved.*

Having established a systematic approach to the characterization of the groundwater system, as described in sections 21.6.2 and 21.6.3, the WR&C specialist will have identified potentially critical design parameters and will have collected the appropriate data needed to analyze the parameters. Using the collected data, the set of testing criteria laid out in section 21.6.3 is applied to the potentially critical design parameters.

The goals of the analysis of the potentially critical design parameters are to:

- Determine which of the potentially critical design parameters are actually critical

- Determine the degree to which each design parameter is critical to the project (e.g., if the dewatering system fails due to a power outage, is a given cut slope in immediate danger of failure, or will take hours or days to reach the point of potential failure)

- Rank the parameters in order of the degree of the critical nature of each parameter (this ranking can then be used to design system redundancy, emergency responses, mitigation measures, etc.)

- Determine if any critical parameters were overlooked

The methods of analysis are often different for different parameters and may consist of something as simple as a “back of the envelope”[13] calculation or professional judgment, or as detailed as a numerical analysis, laboratory testing, or an analog or numerical simulation (such as a physical, scaled-down model of the system or a computer model).

21.7 Construction and L-23 Impacts

For every construction and dam safety project, a CEAP is written to detail the emergency procedures and contact information specific to the project. Every Reclamation dam should have an existing Emergency Action Plan (EAP) for normal operations. The existing EAP should be used and modified to make the CEAP that should be used during the construction of the dam. The known risks are listed, with protocols to mitigate the potential danger to construction support personnel and the downstream Population at Risk. In the event of an emergency, the CEAP should be referenced and followed, including contacting the key decision makers. CEAPs can be written both by Reclamation and by the contractor for the project. It is very important that the contractor’s EAP be reviewed and updated as necessary to include the contact information for the Contracting Officer’s Representative (COR), who is the main contact to represent Reclamation and the Government’s interests in the project.

The CEAP will reference specific monitoring instruments, which are used by the contractor and by Reclamation to monitor the project during construction. The instruments will be listed in a report referred to as an L-23, which will include a schedule for reading the instruments, as well as a protocol for readings that are outside the allowable parameters (e.g. high water pressures, excessive deformations, etc.). When additional instrumentation is installed during construction for the dewatering efforts, the devices should be added to a new L-23 used for construction in conjunction with the CEAP, and clear procedures

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[13] The term ‘back of the envelope’ calculation is a slang terms that generally refers to a very simple calculation that can be done easily and quickly without any significant effort, such as using a calculator, conducting field or laboratory testing, or doing modeling, while still being reasonably accurate.

should be documented for relaying information about the state of the project between the contractor and the COR.

The operation and potential failure of dewatering systems routinely have an effect on the stability of a dam and related structures; therefore, they have an effect on the risk to life and site safety during the construction process. Therefore, adequate instrumentation and observation (including automated instruments with alarm levels set in some cases) are critical elements for construction operations. In some cases, existing instrumentation can be used to supplement the construction monitoring instrumentation. Review the L-23 for each project prior to designing the dewatering system; adjusting the reading schedule for favorably situated existing instrumentation can be time saving and cost effective.

21.8 Water Removal and Control: System Design Considerations

21.8.1 General Description

There are many tools available to the WR&C specialist to:

- Evaluate site conditions and parameters
- Assist in the design of the system

Those tools are analog, analytical, or numerical in nature, and each has its own benefits and limitations. Regardless of which tool is used (a combination of tools is often used), the goal is to understand the site conditions and the site factors that will control the WR&C system effectiveness, and then to design the system to use the site conditions to the advantage of the system.

Dewatering and unwatering systems have many considerations in common, as well as considerations unique to either dewatering or unwatering. Those considerations will, in large part, determine what techniques will be used, what degree of redundancy should be built into the designs, what types of secondary seepage controls may be needed, and how best to instrument and monitor the effectiveness of the system(s).

21.8.2 Analysis and Tools

Analysis methods, and the associated tools available, fall into three broad categories – analog methods, analytical methods, and numerical methods. Analog methods involve using a physical model to represent the system and are not discussed in this chapter. Analytical methods involve mathematical models to represent the system or some aspect of the system. Numerical methods involve using a numerical (digital) computer model to represent the system. The goal of all three methods is the same – to evaluate the system and how it might respond to outside stresses such as excavation, water removal, loading, and similar changes to the existing conditions.

Models simulate what conditions could be like given the conditions and assumptions being modeled. The simulation results are often highly dependent on the amount, type, and accuracy of the data that is input into the model.

21.8.2.1 Analytical Methods

Analytical methods involve collecting field data and using mathematical models to evaluate the data and to estimate how the feature or condition being modeled might respond to changing field conditions. Analytical methods are generally two dimensional, as in x-y or x-z planes, simulations and only evaluate a limited number of parameters in any given simulation. A slope stability analysis would be one example of a commonly used analytical method using a mathematical model to evaluate a field condition and to estimate responses to changes in the field conditions.

Groundwater regimes, by their very nature, must be analyzed in 3D, although for simple groundwater systems or very localized construction projects with a small footprint, a quasi-3D analysis is often sufficient.

Mathematical methods come into play in the evaluation of site conditions and the design of WR&C systems when they are used to evaluate aquifer parameters, which are then used in other mathematical models or numerical models. The commonly used mathematical models in WR&C design and evaluation are covered in section 21.8.3.

21.8.2.2 Numerical Methods

Numerical models also rely on mathematical representation of a parameter in the groundwater regime (similar to an analytical model). Numerical models differ from analytical models in that they integrate many different parameters into one model. Numerical models are capable of quasi-3D or true 3D representation of the groundwater regime; thus, they are capable of evaluating the cumulative responses, as well as individual responses of the system, to multiple external stresses.

Depending on the complexity of the groundwater system, the numerical model could be something as ‘simple’ as an Excel spreadsheet or as detailed as a computer model (such as MODFLOW, FEFLOW, SEEPW[14] or some proprietary model). Numerical models are more data intensive than either of the other two methods and can provide more detailed and complete estimates. They can also be updated continuously as new data is obtained about the system’s responses.

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[14] SEEPW is a Geo-Slope, International proprietary 3D CAD-based finite element seepage model code.

21.8.3 Modeling Approach

In WR&C practice, analytical models are used to approximate the behavior of an existing groundwater system. Analytical models generally involve certain simplifying assumptions, such as homogenous soils and isotropic soil behavior, and generally assume a vertically averaged value for transmissivity. Numerical computer models allow for both spatial and temporal variations in aquifer properties, and they employ boundary conditions and applied stresses defined for each point of the model. Where possible, analytical methods guided by experience and sound reasoning are often the quickest and easiest method of analysis for groundwater flow problems. Instances where the use of a numerical model would be more appropriate are as follows:

- Stratified aquifers: significant spatial variations in hydraulic conductivity or aquifer thickness.
- Aquifer anisotropy and vertical flow: Analytical models assume horizontal groundwater flow, which is unsuitable in cases such as cutoff walls, where the effect of vertical flow is key to the performance of the dewatering system.
- Proximate or irregular boundaries: when the boundaries of a system cannot be assumed to be regular and fairly distant from the site, and, therefore, a flow net is not a suitable model.
- Nonsteady-state or transient analysis: where multiple pumping wells or variations in aquifer properties make the use of the Theis nonequilibrium equation unsuitable.
- Partial penetration: The elongated flow paths and convergence of flows as water is pumped introduce vertical gradients in the aquifer and represent a departure from the radial flow patterns of fully penetrating wells.
- Secondary permeability: significantly higher than the primary permeability of certain low permeable layers.

There are a series of steps for designing a modeling system, which include outlining the problem and determining what mathematical model to use. The steps are:

1. **Define the Need and Purpose.** If an analytical model can be used to solve the problem, the additional effort and expense of a numerical model is not justified. Defining the purpose of the model helps delineate what additional information is required to build the model and helps identify the scope of the model.

2. **Develop the Conceptual Model.** This step involves assembling all of the pertinent geologic, groundwater, and soils information for the area, and developing an understanding of the interaction of those data sets. This step includes appropriating and developing the necessary cross sections to visualize and develop the groundwater model. It also helps clarify which information is still missing and needs to be gathered with additional field exploration. If additional information cannot be obtained, an uncertainty analysis can be defined at this stage to help interpret the model results.

3. **Select the Modeling Program.** There are a number of models available (both public domain and proprietary) to model different problems. It is important to select one that is reliable, familiar, and will meet the purpose of the conceptual model[15].

4. **Construct the Computer Model.** The model is comprised of the aquifer properties, boundary conditions, initial state, and anticipated changes (e.g., recharge, surface water infiltration, etc.)

5. **Verify the Computer Model.** Compare the model outputs with the results from analytical methods, and verify the parameters input into the model. This stage develops confidence in the model and allows the modeler to verify the reasonableness of the model functions.

6. **Calibrate the Computer Model.** This step involves adjusting the aquifer properties to match the known, existing field observations; it is another proof test for the model.

7. **Employ the Model.** Use the model to estimate the outcome and performance of the dewatering system. Completing a parametric analysis with the model enhances understanding of the sensitivity of the model to particular parameters. It also allows the modeler to determine whether additional field exploration or testing is required to determine the realistic range for those properties.

The steps described above are explained in more detail and presented in flow-diagram format in “Standard Guide for Conceptualization and Characterization of Groundwater Systems” (ASTM, 2008) and related ASTM standards.

Three-dimensional software programs commonly used to model, design, and evaluate WR&C systems include both public domain and proprietary software packages. The most commonly used public domain packages include the USGS MODFLOW and FEFLOW packages. Similarly, the most commonly used

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[15] The correct process is to define the problem and select a model code that can address the problem, as opposed to selecting a model code and trying to fit the model code to the problem.

proprietary packages include Schlumberger Water Service's Visual-MODFLOW package, BOSS International's Groundwater Modeling System, and Environmental Simulations, Inc.'s Groundwater Vistas. Additionally, many State water resource agencies have modeling packages specifically design or modified for their State (e.g. California Department of Water Resources, Integrated Water Flow Model, v4.0).

21.8.4 System Design Recommendations

The analysis results will provide the specialist with a set of factors upon which to base a recommendation for the type, size, and components of a WR&C system. The recommendation, along with a draft layout and a draft quantity estimate sheet should be presented to project management no later than at the 30% design milestone. Submitting it earlier may not be practical because the excavation plan and schedule may not be far enough along to provide the information that the specialist needs for a recommendation.

There are many considerations that should go into WR&C system design recommendations. The number of factors to consider, and the potential combinations of factors possible, are as varied as the sites where WR&C systems will be employed. Additionally, at any given site, one or more of the factors may be more critical than the other factors.

The usual factors that will determine which WR&C system (unwatering, dewatering, no control, or a combination) to recommend, as well as the components of the WR&C system (deep wells, sumps, well points, cofferdam, etc.), are:

- Soil characteristics including, but not limited to, density, grading, compaction, amounts and types of silts and/or clays, and layering
- Bedrock including, but not limited to, type, depth, fractures and/or joints, and competency
- Hydrologic characteristics including, but not limited to, static water levels, distance to and type of recharge source (including runoff from storm events), hydraulic conductivity of saturated materials, and boundary conditions
- Excavation characteristics including, but not limited to, depth, size, excavation methods, access, excavation slope supports, excavation sequencing, and duration of open excavations

- Other considerations including, but not limited to, nearby structures, nearby foundations, access to WR&C components, discharge location(s), and potential sources of contamination within the zone of influence of the WR&C system

In Powers et al. (2007), tables 16.1 through 16.3, respectively, summarize when conditions might be favorable to open pumping, as well as unfavorable to open pumping (predrainage or cutoffs preferred), and a checklist for predrainage methods (tables 16.1, 16.2, and 16.3, respectively). These tables provide a guide to an initial starting point for recommending and designing a WR&C system. The best, and often only, guide the specialist has is experience combined with adequate site data.

21.8.5 Dewatering Well Design

Many of the considerations in the design of dewatering wells are the same, regardless of the type of system that will ultimately be employed; and, in some cases, multiple types of systems may be more appropriate than a single type. A design team discussion should be included in the design process to assess the relative importance of the various parameters involved and to verify the assumptions used in the design of the WR&C system(s).

Design considerations should include:

1. **Maximum Depth of the Excavations.** The dewatering goal typically is to lower the water table to a minimum of 5 feet below the lowest excavated surface in order to ensure ‘dry’ working conditions in the excavation. However, depending on the required working conditions in the excavation, lowering the water table by 3 feet may be adequate. Because of well hydraulics and the designed well interference between adjacent wells, the bottom of the wells should be a minimum of 10 feet below the desired water table (or a minimum of 15 feet below the lowest point of the excavation).

2. **Maximum Area to be Dewatered**. Larger areas will require a more robust dewatering system.

3. **Pump Size.** The size of the pump will depend on several factors:

   a. **Anticipated Yield of the Well.** This anticipated yield is based on analytical or modeled estimates of the maximum yield needed for a given well.

   b. **The Total Dynamic Head (TDH).** The TDH that is required, calculated as the distance from the pumping water level to the ground surface + the length of the riser pipe and discharge line (pipe friction loses) + the elevation change from the ground surface to the discharge point + friction losses due to fittings in the pipe (elbow, bends, valves, etc.), and to a lesser extent, the pipe diameter and internal pressure zones.

   c. **Available Power.** Line phase and voltage, if available at the site, may limit the maximum horsepower of the pump.

   d. **Saturated Thickness and Transmissivity of the Materials.** These components will influence the shape of the drawdown cone, how quickly the pumping water level might drop below the pump intake, and the spacing between wells.

4. **Well Diameter.** The well diameter is determined by the pump size and, hence, the pump diameter.

5. **Material Properties.** The characteristics of the materials to be dewatered influence a number of design considerations, which are discussed below.

   a. **Conductivity.** The hydraulic conductivity will influence well spacing and anticipated yields from the wells. All other factors being equal, higher conductivity materials will have wider and shallower drawdown cones than lower conductivity materials. A drop in the conductivity of one order of magnitude will result in an **increase** in the drawdown by about one order of magnitude and a **decrease** in the width of the drawdown cone of about one-half.

   b. **Variability and Extent of Materials.** Due to the typical locations of embankment dams, the native foundation materials encountered are rarely, if ever, uniform or homogeneous over wide areas (much less over the entire site). Embankment materials, along with any zones of fill or waste left over from the construction of the dam or previous construction activities on the dam, are quite different from the native materials and require special considerations. In particular, if any holes are to be drilled in or through the embankment itself, this activity should be performed by a Reclamation drill crew or only under the strictest of oversight and direction of non-Reclamation drill crews (Bureau of Reclamation, 1989; Bureau of Reclamation, 2012).

   c. **Secondary Permeability.** Secondary permeability may be more important and a greater contributor of subsurface flows and/or seepage than the primary permeability of many materials. Secondary permeability is often extremely hard to measure and is seldom uniform over a large site. Secondary permeability is generally best evaluated using multiple aquifer tests over a large areal extent.

d. **Cohesiveness of Materials.** The cohesiveness of subsurface materials will influence the installation methods and the design of the wells; cohesive materials that are not subject to caving may allow for uncased wells or cased wells without filter packs; less cohesive or caving materials will require casing, screens, and filter packed wells.

e. **Gradation.** The grain size distributions of the materials will have a significant impact on the design of the wells in addition to the selection of the type of system to be employed (see figure 21.4.1-1). The amounts of fine-grained materials (silts and clays) will directly impact the need for screens with a small slot size and a corresponding, properly designed filter pack. Predominantly fine-grained materials typically do not gravity drain, so closely spaced wells may be needed. Additionally, even closely spaced wells may not be effective; in that case, the only option is to cut off, reduce, or otherwise control the seepage from the materials (see section 21.8.6).

f. **Filter Pack.** If a filter pack (also called a gravel or sand pack, or a gravel envelope) is used, the gradation of the filter pack should be matched to the formation gradation and screen slot size. The filter pack gradation should be designed to retain 90% of the formation materials. Additionally, the filter pack should have a higher conductivity (as determined by using figures 21.8.5-1 and 21.8.5-2) than the surrounding formation.

6. **Water Chemistry.** Water chemistry is not specifically addressed in this chapter because most WR&C activities are short duration; however, in longer operations, the water chemistry may become an issue.

For example: At the same project discussed previously (sections 21.6.7 and 21.6.8), dewatering operations began more than a year prior to the actual start of excavation activities. During that time, a number of the wells experienced reduced yield capacities due to fouling by iron bacteria (figure 21.8.5-3) and had to be "rehabilitated." Even though they were rehabilitated by cleaning and adding bleach, they never returned to their original capacities – likely because the filter packs were also being fouled, and the chlorination/disinfection was only marginally effective in the filter pack.

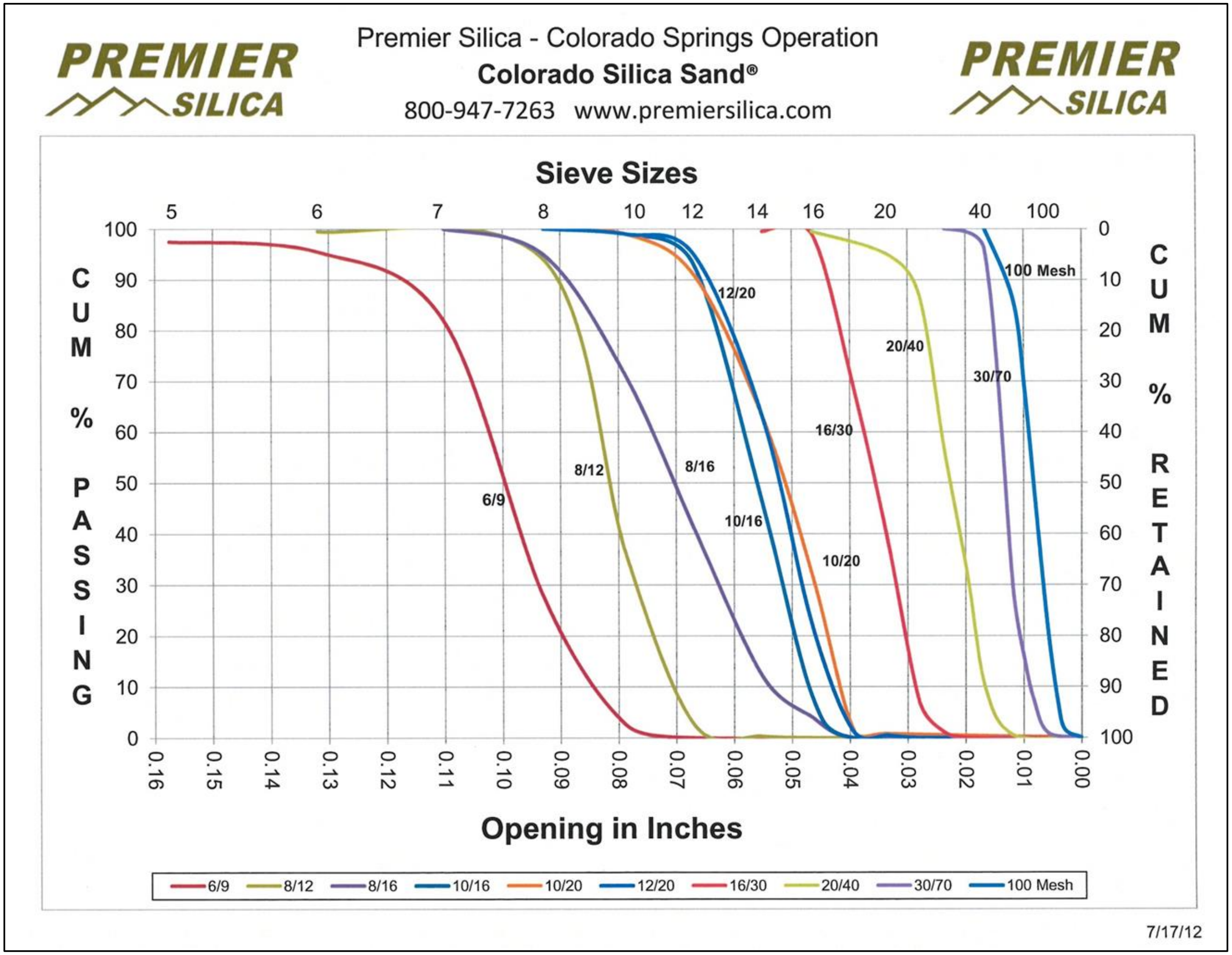
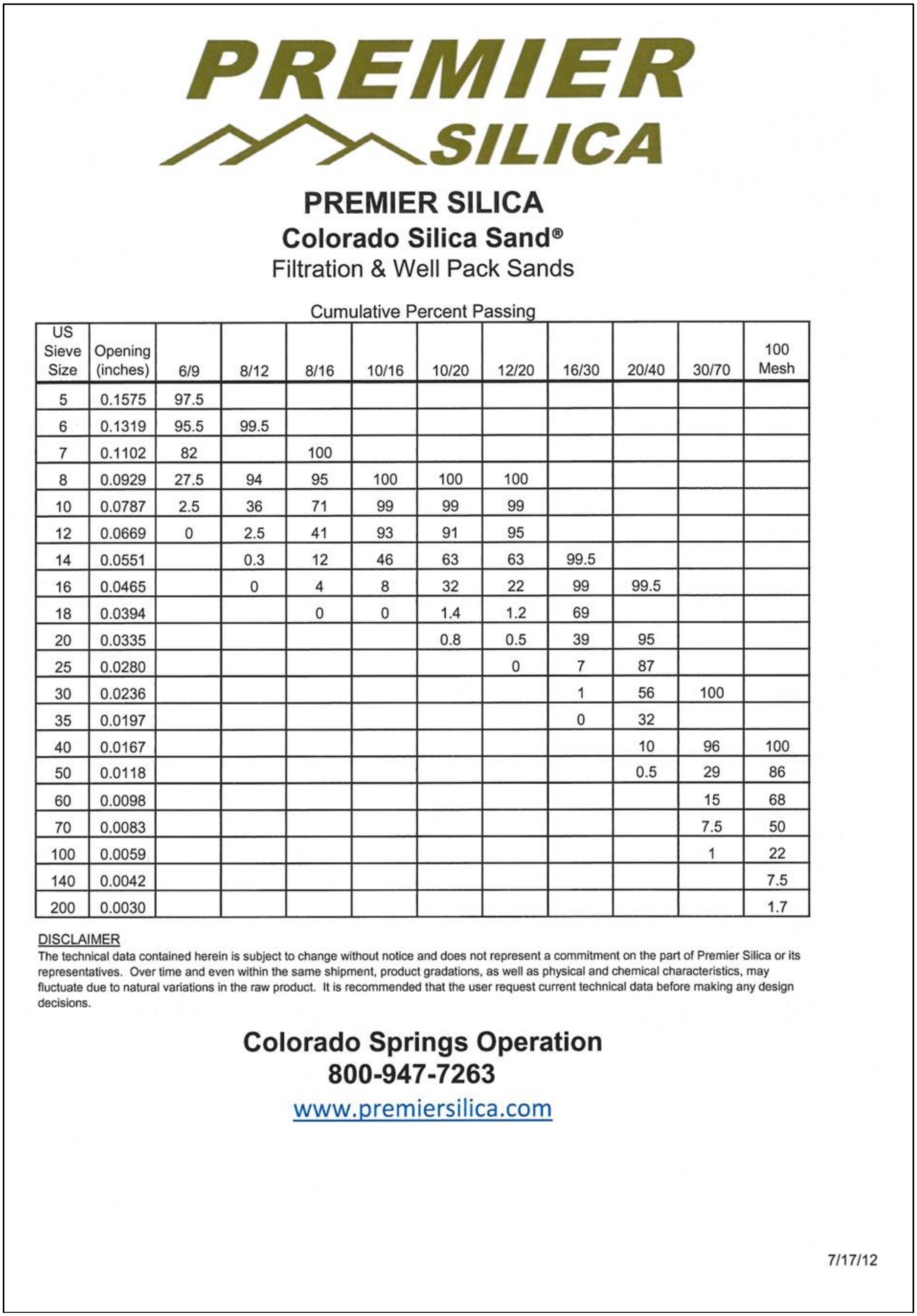


Figure 21.8.5-1 Typical gradation curves for standard Colorado silica sand filter packs; ***K*** of filter pack can be calculated using any of the formulae in section 21.6.6.1 or comparing to figure 21.6.6.1-1 **(reprinted with permission, Johnson Screens, Inc.).**



PREMIER SILICA

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Colorado Silica Sand®

Filtration & Well Pack Sands

Cumulative Percent Passing

US Sieve Size	Opening (inches)	6/9	8/12	8/16	10/16	10/20	12/20	16/30	20/40	30/70	100 Mesh
5	0.1575	97.5									
6	0.1319	95.5	99.5								
7	0.1102	82		100							
8	0.0929	27.5	94	95	100	100	100				
10	0.0787	2.5	36	71	99	99	99				
12	0.0669	0	2.5	41	93	91	95				
14	0.0551		0.3	12	46	63	63	99.5			
16	0.0465		0	4	8	32	22	99	99.5		
18	0.0394			0	0	1.4	1.2	69			
20	0.0335					0.8	0.5	39	95		
25	0.0280						0	7	87		
30	0.0236							1	56	100	
35	0.0197							0	32		
40	0.0167								10	96	100
50	0.0118								0.5	29	86
60	0.0098									15	68
70	0.0083									7.5	50
100	0.0059									1	22
140	0.0042										7.5
200	0.0030										1.7

DISCLAIMER

The technical data contained herein is subject to change without notice and does not represent a commitment on the part of Premier Silica or its representatives. Over time and even within the same shipment, product gradations, as well as physical and chemical characteristics, may fluctuate due to natural variations in the raw product. It is recommended that the user request current technical data before making any design decisions.

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7/17/12

Figure 21.8.5-2 Typical gradation distributions for standard Colorado silica sand filter packs (reprinted with permission, Johnson Screens, Inc.).

(a) Discharge lines installed about 1 year apart

(b) Discharge line from well in service for 1 year

Figure 21.8.5-3 Iron bacteria fouling of discharge lines in dewatering wells; all lines are from the same WR&C system. Discharge varied between 10 and 125 gallons per minute. Pumping was continuous over a period of about 1 year, depending on when the well was installed. (Photos by Ira Terry, Provo Drill Crew Geologist, Reclamation, 2012).

7. **Proposed Excavation Method, Excavation Access, and Cut Slope Support.** Excavation methods such as draglines, clamshell, excavator, scrappers, loaders, and/or dozers will influence the method of WR&C. Excavation access routes will influence the placement of WR&C facilities, discharge lines, settling basins, etc. Ground support in the form of support of cut slopes (sheet piles, soldier beams, lagging, filter blankets, and the like) will influence the placement of WR&C facilities, access to the facilities, drain line layouts, and similar characteristics of the WR&C systems.

8. **Construction schedule and timing**: the length of the construction schedule, the time of year that the excavations will be open and the length of time that the excavations will be open will influence several WR&C design considerations such as; whether the dewatering will require rapid or slow drawdowns, whether pre-drainage is possible, potential impacts from outside sources of recharge, potential impacts from weather related recharge, and potential impacts on the construction schedule from delays in the WR&C operations.

9. **Anthropogenic Concerns.** Although generally not a concern at most dam sites, occasionally, anthropogenic concerns will come into play in the design of WR&C systems and possibly in the excavation plans as well. Anthropogenic features that most often influence excavation designs (and hence, the WR&C designs) include buried or above ground pipelines, utility corridors, roads, existing buildings (such as dam tender homes, pump houses, spillways, gate control systems, etc.), and historical or archeological sites.

10. **Contamination.** Construction WR&C is generally not concerned with contaminant transport issues; however, the possibility that contamination in nearby areas could become mobilized through construction dewatering needs to be evaluated and on- or off-site treatment and disposal may be required. In addition, if contamination is discovered in the discharge waters, plans need to be in place that can be implemented quickly to minimize the spread of the contamination to local water features, as well as to avoid or minimize potential violations of National Discharge Permits requirements.

11. **Development.** Regardless of the type of well or size of well, it is critical to establish the best possible connection between the aquifer materials and the well screen (figure 21.8.5-4). Proper well development is the most important step in the well installation process to establish this connection. The goal of the development process is to remove all the fines from the filter pack (if one is installed) and the immediately adjacent formation materials to produce a uniformly graded zone around the well that will have a higher conductivity than the surrounding formation.

12. **Production Water Disposal.** Common to any type of WR&C system and/or components of the system is the means of transporting the waters produced by the dewatering and unwatering component away from the construction zone and the release of that water. The discharge should be constantly monitored for water quality parameters as indicators of changes in system operations. Commonly monitored parameters include sand content, turbidity, temperature, pH, and conductivity. Other parameters such as dissolved constituents may be added where site conditions warrant it. Consideration should be given to the manifolds and discharge line lengths, routing, sizing, interference with or by other construction activities, etc. Ideally, the discharge lines and manifolds, where possible, should be gravity flow, which means that the lines should be oversized to minimize pressure buildup in the lines and "choke points"[16] that restrict the flows and may cause backups in the lines. Where the water exits the discharge lines, or transitions from one system to another (e.g., going from a discharge pipe to an open channel or settling pond), the flows should be controlled to avoid erosion of manmade or native features.

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[16] A 'choke point' is any kink, bend, constriction, or partial blockage in a discharge line that would limit or hinder the free flow of water through the line, including undersized flow meters and/or valve fittings, and reducing fittings going from a larger to smaller diameter line.

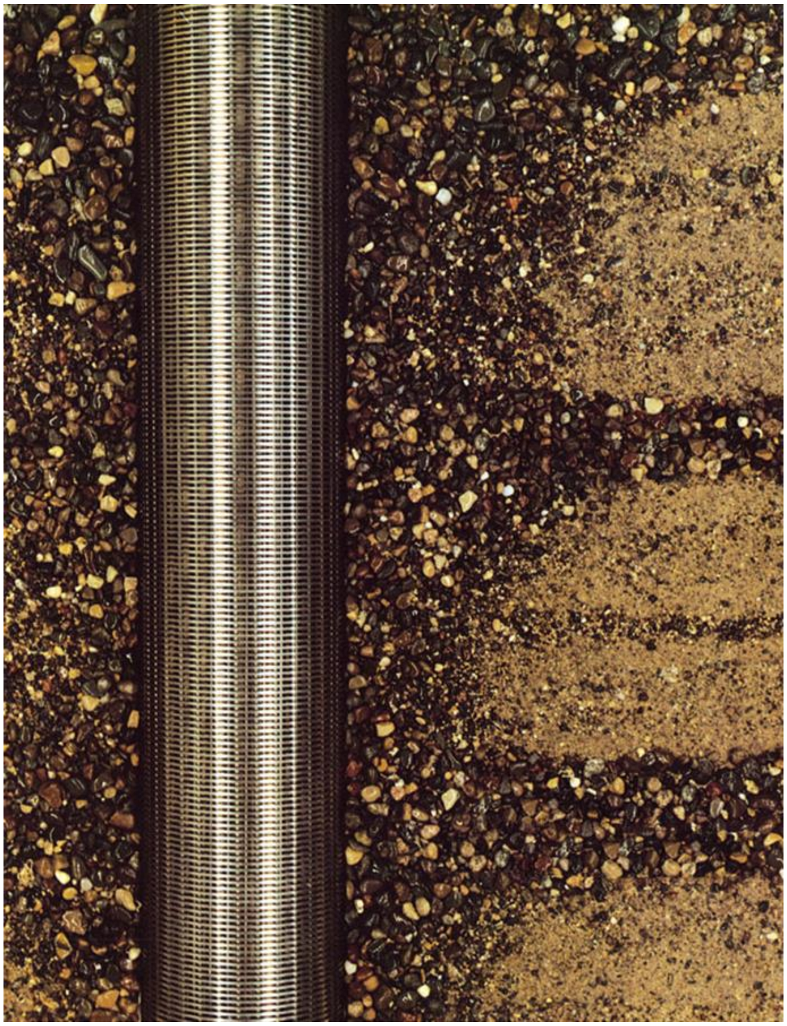

Figure 21.8.5-4. Illustration of a well-developed, uniformly graded filter zone around a well screen (reprinted with permission, Johnson Screens, Inc.).

21.8.5.1 Deep Wells

There are few limits to the possible number, depths, and capacities of individual wells in a deep well system; however, a number of practical limits do exist, which include:

- Dewatering wells should usually be placed outside of the excavation footprint to minimize the potential for damage to, or destruction of, a well from construction equipment.

- Deep wells for dewatering around embankment dams commonly have an 8- to 16-inch-diameter screen with lengths up to 300 feet or more and are generally installed with a filter pack around the screen to prevent the infiltration of foundation materials into the well and to improve the yield of the well. Note: Well diameters, both casings and screens, as well as nominal pump diameters, are not normally given in SI units.

- If geologic and/or excavation conditions require that one or more dewatering wells and/or observation wells be installed within the excavation, special construction features need to be incorporated into the well designs to protect them from construction damage and to allow the well to be lowered as the excavation deepens.

- Geologic conditions within relatively flat alluvial stream valleys can be quite variable for a specific site. Thus, each well system needs to be designed to meet the condition found at the site where the well is to be installed. General designs can be planned for specification purposes, but the specifications need to allow for field modifications to meet site-specific conditions.

- Not all wells in the system will be installed to the same depths, nor will they have the same designed yields. Subsurface conditions will always have some variability associated with them; therefore, adequate and sufficient exploratory investigations prior to the design phase are critical.

- Deep well system design (depths, spacing, screen intervals, etc.) will be influenced by local conditions such as location, extent, types of subsurface materials, potential recharge sources, etc. Excavation plans will be a major factor in the design of the WR&C systems.

- Deep wells are not suitable for low permeability materials and/or where anticipated yields per well are less than about 5 gallons per minute (gpm) (0.011 cubic feet per second [cfs]). However, these wells can be installed with automatic shutoff systems when certain water levels are achieved in the well.

Deep wells, in the simplest of terms, are boreholes below the usual operational depths of well points and sumps that are equipped with a submersible pump. They may or may not be cased, screened, and filter packed. They typically vary from 3 inches to 24 inches in diameter and range from 20 feet to hundreds of feet deep, and their yields can vary from 10ths of a gallon to thousands of gallons per minute. Because submersible pumps do not operate by suction, they do not suffer from the depth restrictions common to well points and eductor wells. However, they are limited by the TDH of the well, along with the intake velocity of the screen, and the diameter of the well, to name just a few of the more important design considerations in pump sizing and selection.

Commonly available pumps come in nominal diameters of 4 inches, 6 inches, 8 inches, and 10 inches. Smaller pumps designed to fit into 2-inch-diameter wells are available, as are pumps up to a nominal diameter of 18 inches. However,

these smaller and larger diameter pumps are usually only used in specialized circumstances that are seldom found at embankment dams.
Deep wells are more suitable for conditions of:

- Higher conductivity materials
- Loose, uniform granular soils
- Relatively thick saturated thicknesses
- High groundwater heads
- Artesian conditions
- Proximity to recharge sources
- Greater required drawdowns

Deep wells can be installed using many different materials and in many different configurations. There is no "one size fits all" design for deep wells; although, in the case of embankment dams, the vast majority of dewatering wells are short-term, temporary wells with a simple purpose: to pump as much water as possible, draw down the potentiometric/water table surface as much and as quickly as possible, and keep it drawn down while the excavation is open. This makes the design of deep wells for WR&C systems relatively simple, and the primary considerations become:

1. Required depth to attain the necessary drawdowns.

2. Required size to accommodate the proper pump size for the necessary yield.

3. Screen length and slot size to achieve the necessary yield.

4. Whether the well will be artificially or naturally developed.

The salient features of a deep well are illustrated in figure 21.8.5.1-1. State regulations regarding certain design criteria for temporary well (such as whether or not a surface sanitary seal is required (and, if so, how deep it will be), what materials can be used for annular backfill, and so forth) vary from State to State, so it is important to check the State and local regulations of the project area before designing a WR&C system meeting the 60% design criteria.

Deep wells are suitable for use in combination with well-point systems and/or eductor well points. Deep wells may be used in conjunction with a vacuum system to dewater small, deep excavations for tunnels, shafts, or caissons sunk in relatively fine-grained or stratified pervious soils or rock below the groundwater table. The addition of a vacuum to the well screen and filter pack can increase the hydraulic gradient to the well and can create a vacuum within the surrounding soil that will prevent or minimize seepage from perched water into the excavation. Installations of this type require adequate vacuum capacity to ensure efficient operations of the system

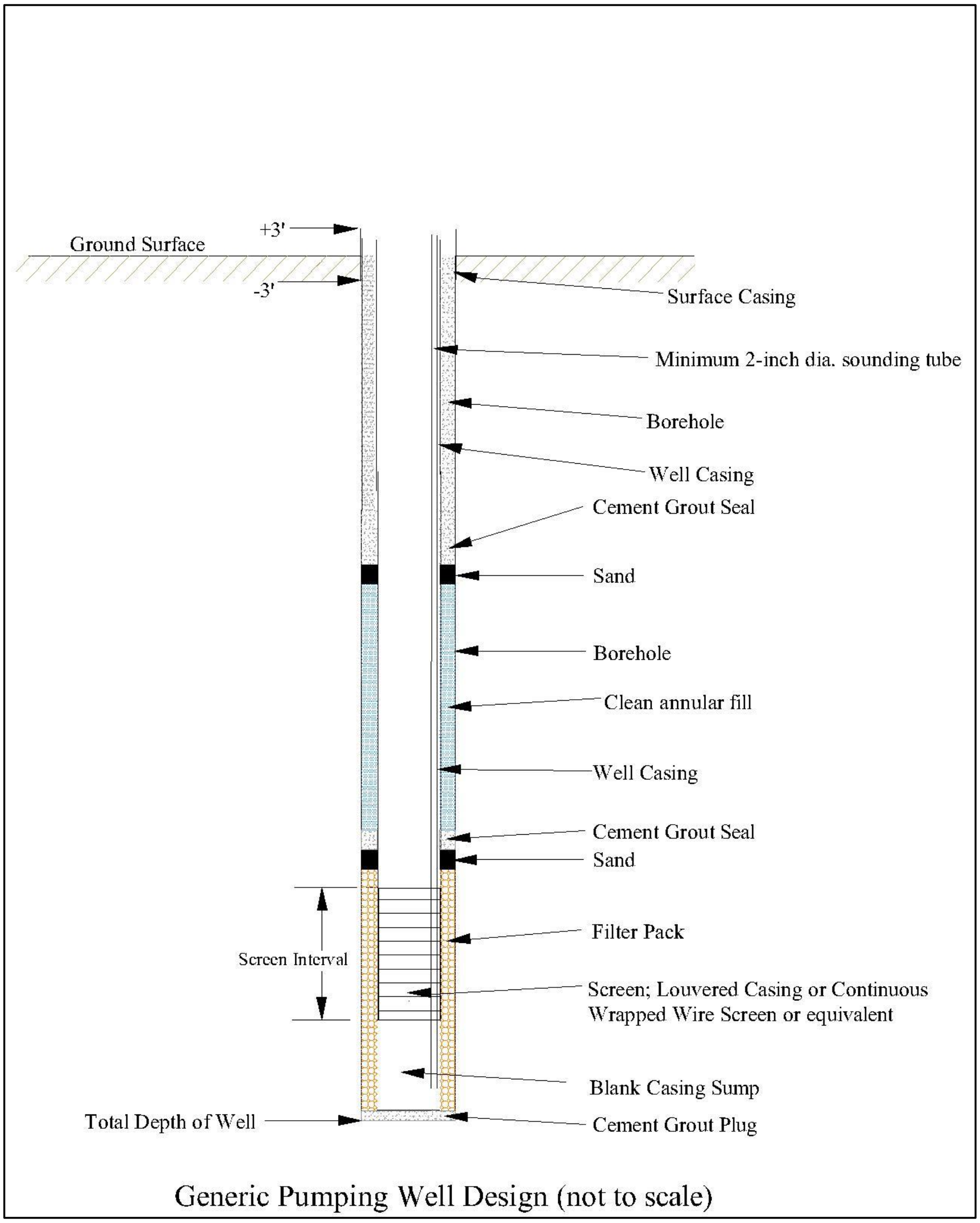

Figure 21.8.5.1-1. Generic well design illustrating the salient features of a permanent dewatering well. Casing and screen can be any suitable material. Expanded sump at the bottom is required to house the pump in order to attain maximum drawdown in the well. Screen slot size and filter pack (if needed) must be sized appropriately for the material to be dewatered. Temporary dewatering wells may or may not require all or some of the features shown, depending on the applicable State regulations.

Specialized forms of deep wells are horizontally directionally drilled wells. These types of wells are advantageous where traditional drill rigs cannot gain access, where there is limited surface access, for dewatering landslide and/or mass movement materials, for targeting specific thin layers, and where existing structures present obstacles to other methods. While not commonly employed in construction of embankment dam modifications, they remain a viable option when conditions warrant their use.

Dewatering wells and well systems need to be designed to dewater a site and maintain the dewatered conditions reliably over an extended period of time. The wells should be deep enough to lower the water levels to some desired depth (typically 3 to 5 feet at a minimum) below the lowest part of the excavation. The wells should be able to operate continuously while the excavation(s) are open. The wells should be capable of pumping the anticipated amounts of water, and the discharge system should be capable of moving the anticipated yields to a discharge point outside the construction zone.

Additionally, the wells should not produce a lot of fines (sanding) in the discharge. Excessive amounts of sand and/or fines, greater than about 20 parts per million (ppm) in any individual well, can damage or destroy the pump. Sanding rates of more than 50 ppm from one or more wells could indicate potentially harmful piping conditions in the foundation of the dam if any wells are in or adjacent to the dam foundation. A foundation piping failure mode should be considered when developing the CEAP. When excessive sanding rates occur in any well, the COR should be notified immediately.

21.8.5.2 Well Points

Conventional well-point systems consist of one or more series/sets of well points having 1½- or 2-inch-diameter riser pipes; installed in a line, circle, or other pattern; at spacings between about 3 and 10 feet (figure 21.8.5.2-1). The risers are connected to a common header pumped with one or more well-point pumps (figure 21.8.5.2-1). The screened well points generally range in size from 2 to 4 inches in diameter and 2 to 5 feet in length and are constructed with either closed ends or self-jetting tips (figure 21.8.5.2-2). They may or may not be surrounded with a filter pack, depending on the type of soil drained. Well-point screens and riser pipes may be as large as 6 inches (not typical) and as long as 25 feet in certain situations. A well-point pump uses a combined vacuum and a centrifugal pump connected to the header to produce a vacuum in the system and to pump out the water that drains to the well points.

Figure 21.8.5.2-1. Single stage (one layer) well-point system (reprinted with permission of Shortflo dewatering system, Groundforce, UK).

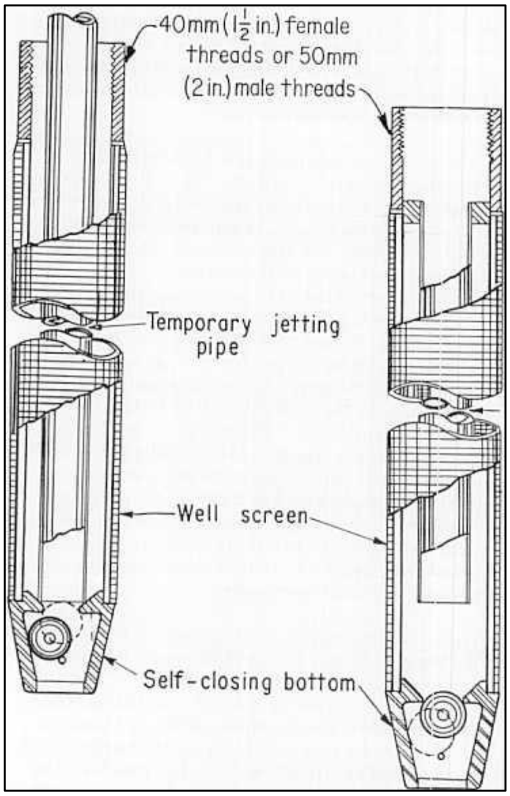

Figure 21.8.5-2-2. Typical well points equipped with jetting tips (figure 14-3, Reclamation, 1995).

Well points are particularly suitable for conditions of:

- Fine-grained materials
- Low permeability soils
- Shallow excavations requiring minimal dewatering (<15 ft)
- Shallow dewatering over large areas

A well-point system is usually the most practical method for dewatering where the site is accessible and where the excavation and water-bearing strata to be drained are not too deep. For large or deep excavations where the depth of excavation is more than 30 or 40 feet, or where artesian pressure in a deep aquifer must be reduced, it may be more practical to use eductor-type well points or deep wells as the primary method of dewatering and use well points as a supplementary method if localized dewatering is needed. Well points are more suitable than deep wells where the submergence available for the well screens is small and close spacing is required to intercept seepage.

Silts and sandy silts ($\boldsymbol{D}_{10}$ = 0.002 inch) with low permeabilities (figure 21.4.1-1) cannot be drained successfully by gravity methods, but such soils can often be stabilized by a vacuum well-point system. A vacuum well-point system is a conventional well system in which a partial vacuum is maintained in the filter pack around the well point and riser pipe. This vacuum will increase the hydraulic gradient towards the well points and will improve drainage and stabilization of the surrounding soil. Relatively little vacuum effect can be obtained with a well-point system if the lift is more than about 15 feet. The effective lift of a well-point system will also decrease with increasing elevation - the general rule of thumb, as stated by most authors, is about 1 foot of decreased lift for each 1,000 feet of elevation gain above mean sea level.

Well-point systems are particularly suitable as supplementary dewatering systems when combined with deep wells because they are easy to install, can be installed relatively quickly, and can be installed in areas that might be inaccessible to drill rigs.

The design of well-point systems is essentially the same as for systems using deep wells, except when considering the advantages and limitations of well points. Well-point systems have a number of advantages and disadvantages.
Advantages:

- Well-point systems can be installed outside of the construction zone to intercept groundwater flows.

- Well points can be installed inside of excavations to spot-dewater areas that are slow to drain.

- Well points can be installed by driving (not recommended), pushing, drilling, or jetting.

Disadvantages:

- Adequate space for the well points, the discharge header, and the well-point pump with sufficient clearance for construction equipment is needed to minimize the potential for damage to, or destruction of, one or more components of the system from construction equipment.

- Individual well points will not have large yields; however, depending on the capacity of the well-point pump, a system could have substantial yields. Well-point systems are not suitable for removing large quantities of water, and booster pumps may be required to lift the water produced from deeper excavations.

- The most significant disadvantage is that the effective depth of conventional and vacuum systems is around 15 feet of lift.

Well-point systems have many of the same performance considerations as deep wells. They need to be designed to dewater a site and maintain the dewatered conditions while the excavation is open, so each well point series/set needs to be designed to operate reliably over an extended period of time. Each well-point system, whether used individually, staged, or as a supplement to other dewatering methods should penetrate a significant portion of the saturated materials. The wells should be able to operate 24/7 while the excavation is open. The well-point system should be capable of pumping the anticipated amounts of water, and the discharge system(s) should be capable of moving the anticipated yields to a discharge point outside the construction zone.

Additionally, the well points, either individually or as a system, should not produce a lot of fines (sanding) in the discharge. Excessive amounts of sand and/or fines can damage or destroy the pump. Excessive amounts of sanding from one or more wells could indicate potentially harmful piping conditions in the foundation of the dam if any wells are in or adjacent to the dam foundation.

Well-point systems are suitable for use in combination with deep wells and/or eductor well-point systems.

21.8.5.3 Eductor Well Points

An eductor (or eductor-jet pump) system is a system that uses water or air under high velocity to create a vacuum in the well point, causing a suction from the Venturi effect, which draws in larger quantities of water from the surrounding materials. The eductor jet consists of tapered nozzle installed in a small-diameter well or a well point screen and attached to a eductor-jet pump installed at the end of double riser pipes, a pressure pipe to supply the eductor jet, and another pipe for the discharge from the eductor pump. Eductor systems are capable of lowering the water table as much as 100 feet from the top of the excavation (USACE, 2004). Eductor well points are installed in the same manner as conventional well points with a filter pack as needed. Two separate headers are required: one header to supply water under pressure to the eductors, and the other header for the return flow from the well points (figure 21.8.5.3-1). Because of the Venturi effect, eductor well points have a greater effective lift (up to 100 feet of lift) than well points or vacuum well points. Applications of eductor systems are similar to both well-point systems and deep wells in that they can be closely spaced (like well points) and can dewater to greater depths than well-point systems (like deep wells).

Eductor well-point systems are most effective for deep excavations requiring minimal dewatering, due to low permeability, and fine-grained soils.

Eductor systems have all of the same design considerations as well points, except that they cannot be driven or pushed; they can only be drilled or jetted. In addition to those design considerations, eductor systems have the additional considerations:

- They have power needs three to five times greater than those of well points or deep wells (Powers et al., 2007; p. 340).
- They are labor and maintenance intensive (Powers et al., 2007; p. 336).
- They require a large length of pipe for both the pressure lines and the return flow lines (Powers et al., 2007; p. 336).
- They require a large amount of water if the return flow cannot be filtered and recirculated.

Eductor systems, like well-point systems, need to be designed to dewater a site and maintain the dewatered conditions while the excavation is open, so each well needs to be designed to operate reliably over an extended period of time. The wells should be able to operate continuously while the excavation is open. The wells should be capable of pumping the anticipated amounts of water, and the discharge system should be capable of moving the anticipated yields to a discharge point well outside the construction zone.

Wells with a properly designed screen slot size and filter pack (if needed) should not produce a lot of fines (referred to as ‘sanding’) in the discharge. Excessive amounts of sand and/or fines can clog a filtration system and damage or destroy a recirculation pump. Excessive amounts of sanding from one or more wells could indicate potentially harmful piping conditions in the foundation of the dam if any wells are in or adjacent to the dam foundation.

(a) High pressure and extraction pumps.

(b)

Figure 21.8.5.3-1. (a) Dewatering operation for the Many Farms Dam outlet structure, Arizona. Eight-inch supply line and 14-inch nipples attached to eductor wells (photo by Dave Gates, 2000). (b) Dewatering well-point system at the Mormon Island Auxiliary Dam keyblock excavation (photo by Jonathan Harris, 2013).

Eductor well-point systems are suitable for use in combination with well points (figure 21.8.5.3-2) and/or deep wells.

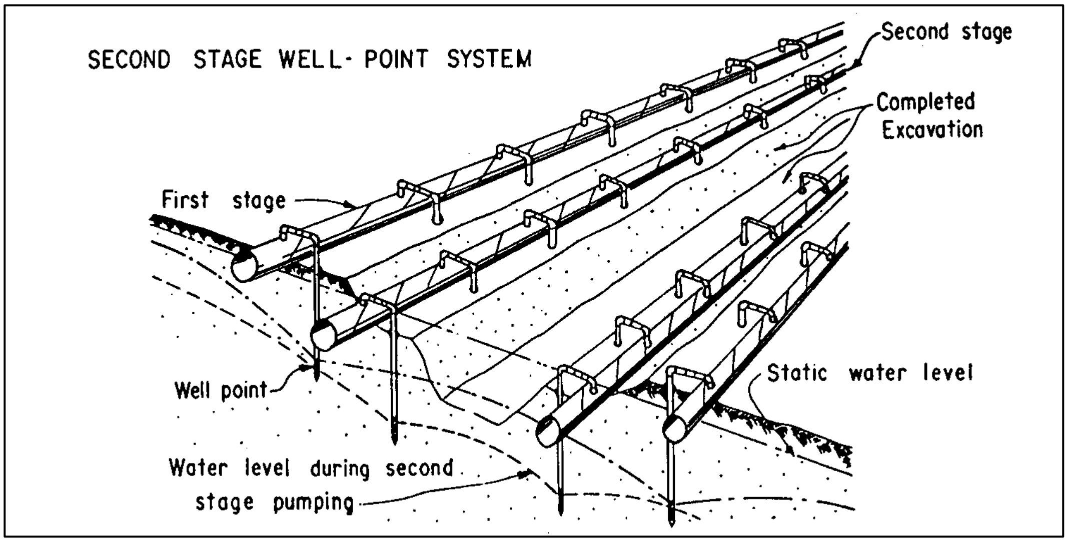

Figure 21.8.5.3-2. Multistage (two layers) well-point dewatering system (Reclamation, 1995).

21.8.5.4 Sumps, Trenches, and Drain Systems

Sumps, trenches, and other open pumping features can be installed in the bottom of an excavation as a means to direct and collect flows where surface water is anticipated. They can also be used to help maintain dewatered and unwatered conditions in the excavation by capturing and removing potential sources of "recharge" or to add additional water removal capability in specific locations where other water removal systems may be impractical. Sumping can be a reasonable alternative to dewatering in fine-grained materials (as long as soil stability can be maintained) because it is easy to maintain adequate discharge requirements. Often, these systems are all that is needed to intercept the runoff before it reaches the excavation rim and to channel it away from the site or into sumps. These systems are very flexible and easily conformable to the layout and changing construction conditions. These systems are relatively inexpensive and can be installed relatively quickly on an "as needed" basis.

Sand drains are a specialized form of open control of water. Sand drains (that can include perforated pipe) can consist of a driven or drilled hole, or an excavated trench that is filled with sand to intercept seepage or perched water in an upper water-bearing stratum and move it to a lower, more permeable stratum that is being actively dewatered by other means.

Sumps, trenches, and open pumping should generally not be considered as the primary dewatering method when the groundwater head must be lowered more than a couple of feet. However, when used as a part of an unwatering system, they can very effective when used with other dewatering methods. In many cases, sumping is used as a secondary method of seepage control in localized areas.

Sumps are most useful for condition of:

- Diverting overland flow (i.e., runoff) from precipitation events
- Excavation requiring minimal dewatering

21.8.5.5 Observation Wells and Piezometers

Observation wells and/or piezometers are a critical part of any WR&C operation that penetrates the water table to any significant degree – either in depth, or in areal extent, or both. A monitoring system should be an integral component of any WR&C system. Observation wells and/or piezometers are the only way to obtain accurate and reliable water or potentiometric levels in the project area before and during construction. The primary difference between observation wells and piezometers is that where observation wells are typically screened across several material types and water-bearing zones, piezometers are typically screened in only one specific water-bearing zone.

The term piezometer is also used in some references to refer to the pressure transducer that is used down hole to measure and record pressure changes due to changes in water levels in the hole. Those measurements can then be converted to feet of water above the sensor and, thus, calculate the water level and changes in the water level in the hole. This type of piezometer is discussed later in Section 21.8.10. Piezometer, as used in this section, refers to an observation well that is screened in a discrete water-bearing zone as opposed to an observation well that is screened over multiple water-bearing zones.

Observation wells and piezometers are critical to WR&C activities and have many of the same objectives, which are:

1. Monitor initial site conditions for use in the WR&C design.

2. Monitor the decline in the water table or potentiometric head during predrainage prior to initiation of excavation activities.

3. Monitor the water levels in and around the construction zone while the excavation is open.

4. Identify dewatering wells that have production rates that have dropped off for reasons other than a lowered water table.

5. Identify rises or fluctuations in the water table, or portions of the water table, that might indicate changing conditions before they become a problem in the excavation zone.

In addition to the above objectives, piezometers monitor water levels and pore pressures in discrete water-bearing units, such as perched water zones or fine-grained materials that are less likely to drain and, thus, may cause seepage problems. An added advantage of piezometers is that if they are arranged in a triangular pattern and are located are in the same water-bearing unit, then they also can be used to determine the hydraulic gradient and the direction of flow. If two or more piezometers are installed in the same borehole (nested piezometers, or piezometer nest), they can be used to determine the vertical gradients between units as well.

Observation wells and piezometers need to be located stratigraphically to effectively monitor the effect of the dewatering system on the groundwater regime. They need to be as close as possible to the deepest area of excavation but not be in the way of the construction operations. They should not be too close to the actual dewatering system because this might misrepresent the dewatering effect in the center of the excavation.

Because observation wells and piezometers depend on good communication between the screen and the water-bearing units, it is equally critical that they are installed and developed properly (just like pumping wells). Any drilling tool or method that will, or tends to, smear the borehole walls should be avoided. Jetting or rotary methods are best suited for installation of observation wells and piezometers. If drilling fluids are necessary, biodegradable additives should be used where State and local regulations permit, and breakdown additives should be used during development.

The salient features of an observation well and a piezometer are illustrated in figures 21.8.5.5-1 and 21.8.5.5-2, respectively. State regulations regarding certain design criteria for temporary wells (such as whether or not a surface sanitary seal is required and, if so, how deep it will be, what materials can be used for annular backfill, and so forth) vary from State to State, so it is important to check the State regulations of the project area before designing observation well and/or piezometer arrays meeting the 60% design criteria. Piezometer design and construction are addressed in *Design Standards No. 13 – Embankment Dams,* Chapter 11, "Instrumentation" (Reclamation, 2014b).

Additionally, the specialist should consult with other design groups, such as the instrumentation group, to determine if there are any existing piezometers that could be incorporated into the observation well/piezometer array. The specialist should also consult with the project leader to determine if any of the units in the observation well/piezometer arrays should be maintained following construction as part of the dam's permanent monitoring system. With some planning, wells installed as part of the data gathering phase can be used later as part of the observation well arrays during the construction phase.

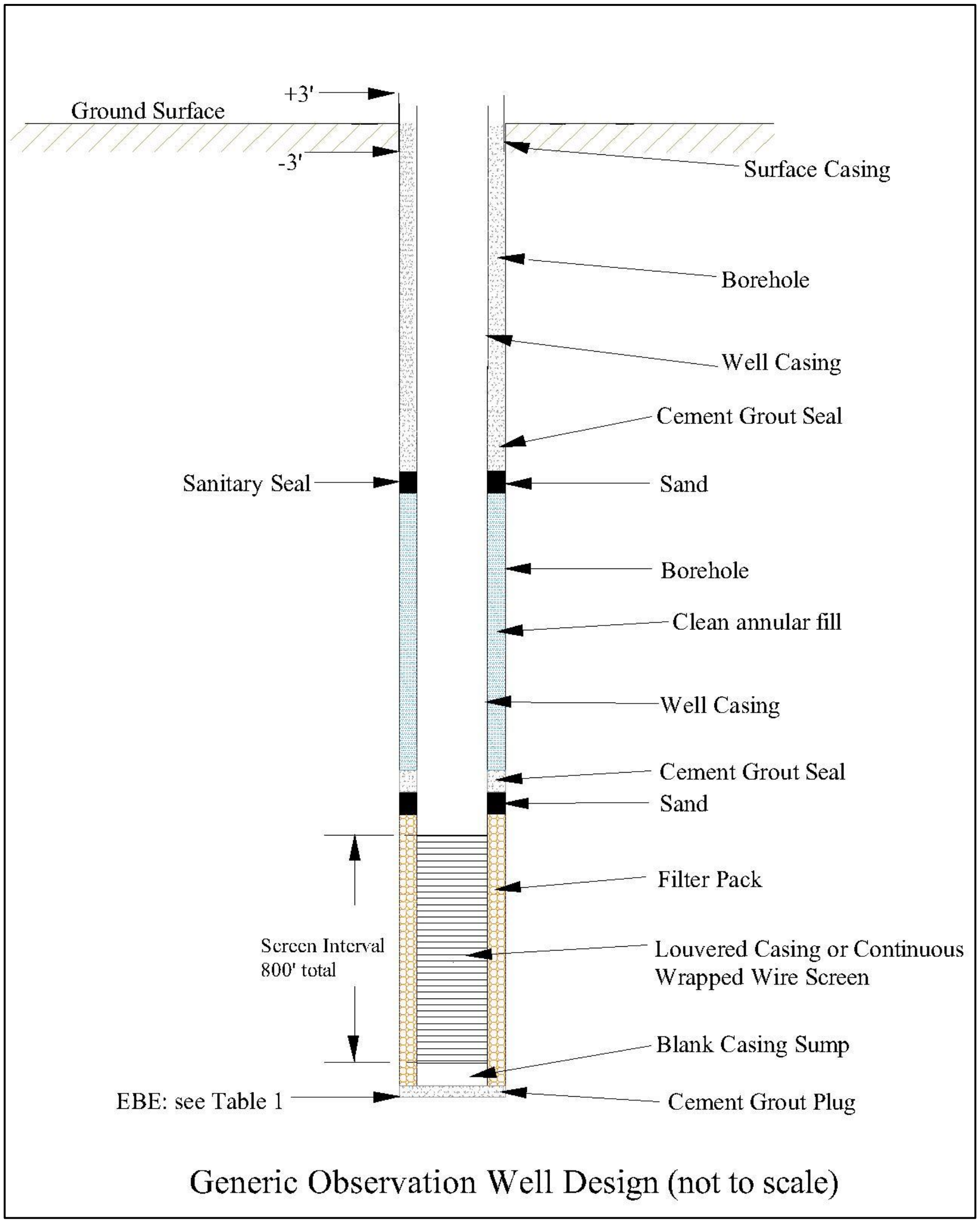

Figure 21.8.5.5-1. Generic well design illustrating the salient features of a permanent observation well. Casing and screen can be any suitable material; screen slot size and filter pack (if needed) should be sized appropriately for the surrounding material. Temporary observation wells would not necessarily require the surface sanitary seal or the cement grout plug at the bottom of the well. Other components may or may not be required by any particular State regulations.

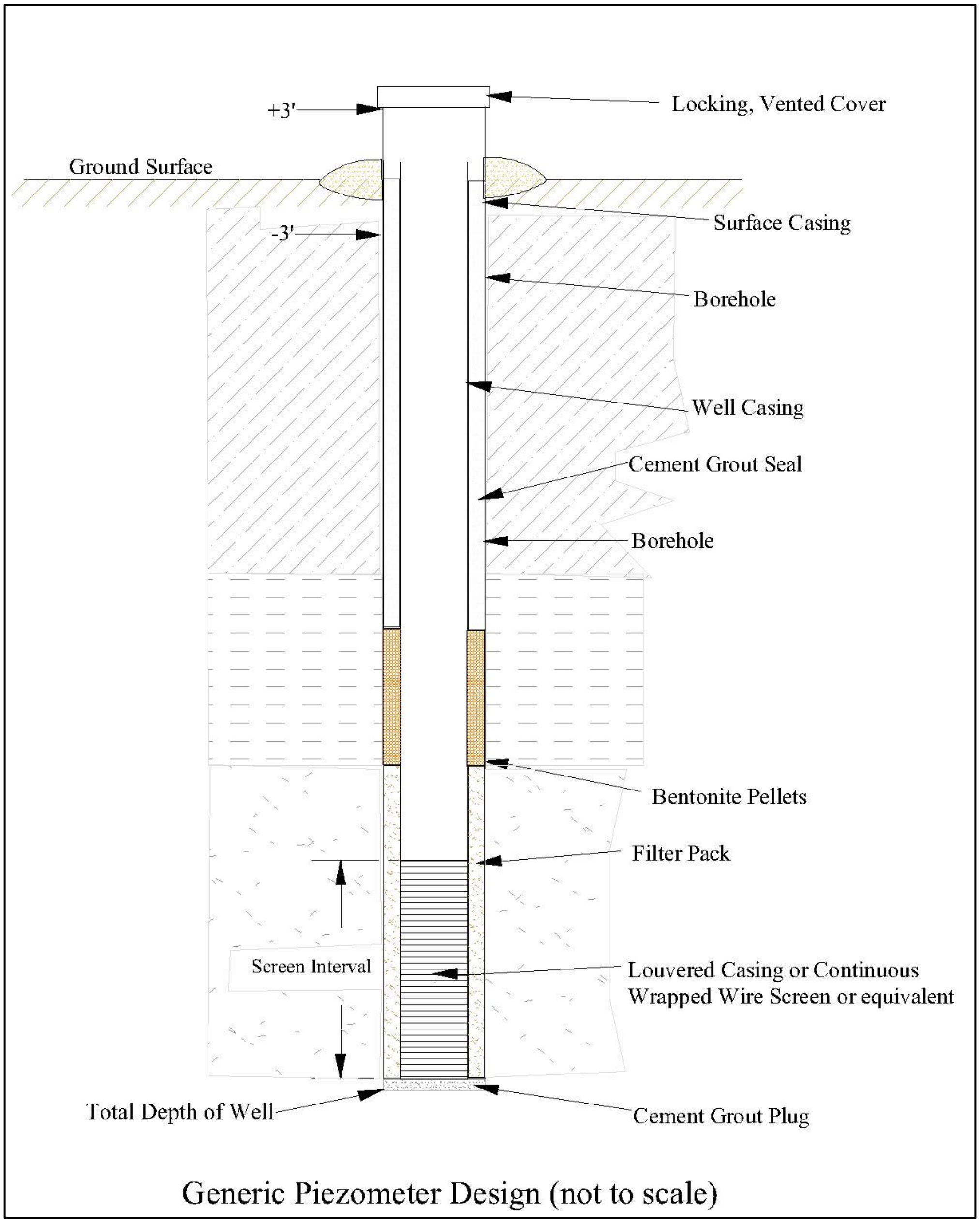

Figure 21.8.5.5-2. Generic design illustrating the salient features of a permanent piezometer. Casing and screen can be any suitable material; screen slot size and filter pack (if needed) should be sized appropriately for the material in the water-bearing zone to be monitored. Temporary piezometers would not necessarily require the surface sanitary seal. Other components may or may not be required by any particular State regulations.

21.8.5.6 Pressure Relief Wells

A pressure relief well is a special purpose well used primarily to reduce pressures in artesian aquifers, thereby reducing or relieving upward leakage of groundwater through the overlying materials and/or to reduce or eliminate hydraulic uplift beneath the floor of the excavation ("blowout"[17]) or below foundations until such time as the excavation is backfilled. Dewatering (i.e., desaturation) of the artesian aquifer is not necessarily achievable or desirable.

Any type of well, including deep wells, eductor well points, and even normal well points under very specific conditions, can be used for pressure relief as long as the well can be properly screened in only the artesian aquifer. The choice of well type depends more on the function of depth to the artesian aquifer and how much pressure has to be relieved than on the type of well used.

Long-term pressure relief wells should be gravity wells, whenever possible, because maintenance of pumps, etc., in the long term is not especially feasible. Such pressure relief well design is beyond the scope of this chapter.

21.8.5.7 Vacuum Pressure Relief Wells

Vacuum pressure relief wells are also special purpose wells that are very similar to pressure relief wells. The primary differences between the two wells are that vacuum pressure relief wells (also called vacuum assisted pressure relief wells) have a vacuum pump in tandem with the water pump, and their primary objective is to relieve pressures in low-permeability materials.

As shown in figure 21.4.1-1, fine-grained materials do not drain easily, and depending on local conditions, it may not be necessary to actually dewater them; just relieving the pore pressures in them may be sufficient. In the case of a saturated fine-grained unit that daylights in an excavation, just relieving the pore pressures behind the open face and using a sump to collect the discharge water may be all that is needed to reduce seepage from the unit and to stabilize the slope. Application of a vacuum can, in some instances, significantly improve the performance of wells in fine-grained materials: "Vacuum can increase well yield from low hydraulic conductivity formations by as much as 20%" (Powers et al., 2007; section 18.7).

Vacuum assist is most effective in closely spaced wells in fine-grained materials. As such, it is suitable for well points and eductor well points. Although vacuum assist would also benefit deep wells, it would be impractical and costly to install deep wells on 5- to 15-foot centers.

21.8.6 Unwatering and Water Control Designs

The purpose of unwatering systems is to control and remove surface water from ponding, either from precipitation events or slow seepage from saturated, very

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[17] 'Blowout' is a construction term that generally refers to upward hydrostatic pressures beneath the floor of an excavation or constructed pad on the bottom of the excavation uplifting or rupturing the excavation floor or constructed pad.

fine-grained sediments exposed in the excavation. Therefore, their use may be temporary and intermittent, and the quantities of water removed may be highly variable. The only necessary performance parameter is to locate them so that they can intercept, channel, and remove surface waters from within and around the excavation.

The use of sumps, drains, open pumping, and other means of controlling standing water or seepage into an excavation that cannot be captured or controlled using other methods generally falls into the category of unwatering. Precipitation or flowing surface water may be the primary source of standing water in the excavation, but when slow seepage from saturated, very fine-grained materials is present, it can also be a significant source. Small seams or lenses of granular materials may also be more effectively dewatered/unwatered using sumps and drains than with wells

There are no standard "designs" for unwatering systems. Each system has to be tailored to the conditions at the site and expected events that might cause standing water to accumulate. Unwatering sumps, trenches, and open plumbing are installed where and when needed, as opposed to being planned and installed ahead of time. If conditions are likely to require unwatering sumps or trenches in the bottom of an excavation, a general plan can be formulated ahead of time and be ready to implement when needed.

Disadvantages of a sump unwatering system are: (1) slowness in drainage of the slopes; (2) potentially wet conditions during excavation and backfilling, which may impede construction and adversely affect the subgrade soil; and (3) space requirements for drains, ditches, sumps, and pumps.

Sumps, trenches, and other open pumping features can be installed in the bottom of an excavation as a means to direct and collect flows where surface water is anticipated. They can also be used to help maintain dewatered conditions in the excavation by capturing and removing potential sources of recharge or to add additional water removal capability in specific locations where other water removal systems may be impractical or inefficient. These systems are very flexible and easily conformable to the layout and changing construction conditions. In addition, they are relatively inexpensive.

Unwatering sumps and trenches are particularly effective in diverting overland flow (i.e., runoff) from precipitation events away from the excavation. Often, these systems are all that is needed to intercept the runoff before it reaches the excavation rim and to channel it away from the site or into sumps. If site conditions permit, pumping may not be needed.

Sumps and trenches may be nothing more than open holes and ditches. However, if a significant amount of water is anticipated, the sumps can be filled or lined with gravel or some other porous material, and a trash pump can be installed inside a perforated culvert pipe in the sump. Likewise, trenches could be filled with gravel, a perforated drain pipe could be buried in the trench, the trench could be lined with a geotextile, or a combination of methods can be used. The system can be tailored to the site conditions. Contractors who install and maintain these systems generally know what methods work well for local conditions.

Sumps, trenches, and open pumping should not be considered as the primary dewatering method when the groundwater head must be lowered more than a few feet, depending on local conditions. However, unwatering methods can be very effective when used with dewatering.

21.8.6.1 Ditches and Drains

Ditches and drains would be most appropriate along the base of slopes where seepage may occur or may be a problem if it does occur, but the seepage is not enough to warrant the installation of a vacuum pressure relief system. They are usually installed as needed and may be very temporary or present during the whole time the excavation is open. If seepage is anticipated, the specialist should consult with the excavation designer(s) to make sure that there is adequate space in the bottom of the excavation, or at the base of any cut slope, for ditches or drains.

Ditches and drains can be as simple as a trench along the base of a slope (a ditch) that collects seepage or runoff (figure 21.8.6.1-1) from the slope and channels it somewhere – either out of the excavation or into a sump – or as elaborate as a geotextile-lined trench (a drain) that has a drain pipe and is backfilled with gravel or some other drainage media. The size is variable and dependent on the flows that need to be managed.

Figure 21.8.6.1-1. Lined trench/ditch at the base of a slope. Slope erosion is also controlled by a mulch covering on the slope and a silt fence near the toe of the slope (photo from State of California Department of Transportation, 2003).

A special type of drain would be a well point or length of screen driven horizontally into a slope or vertical wall to relieve pore pressures and control water level buildup behind a cutoff wall, retaining wall, or other structure necessary to keep an excavation open.

21.8.6.2 Sumps

A sump is a shallow excavation or depression with a pump of some type. Pumps can be a variety of sizes and types; it all depends on the anticipated volume of water to be managed and the characteristics of the water (e.g., how much suspended sediment it contains). If pumping is anticipated to be intermittent, the pump can be equipped with some sort of float switch or operated manually as needed. If a significant amount of water is anticipated, the sumps can be filled or lined with gravel or some other porous material, and a trash pump can be installed inside a perforated culvert pipe set vertically in the sump.

Water is usually channeled to a sump through ditches and drains. Boils in the bottom of an excavation should raise a concern that uncontrolled seepage may be affecting infiltration and should be monitored for the initiation of internal erosion. The system can be tailored to the site conditions and easily adapted to local and/or changing conditions. Contractors that are installing and maintaining this type of system generally know what methods work well for local conditions.

21.8.6.3 Vertical Sand Drains

Vertical sand drains are a passive method of draining water from one elevated high-permeability material to a lower high-permeability material through an intervening low-permeability material. The objective of a vertical sand drain is to create a pathway for water in an upper water-bearing unit to drain down into a lower water-bearing unit that is under lower pressure. This would facilitate dewatering of the upper unit, particularly if the lower unit had a higher horizontal conductivity and was under lower pressure. For example, 12-inch-diameter sand drain packed with a clean filter sand with a K of 1,000 gallons per day per square foot (or 7,480 feet per day) can reportedly transmit up to 0.5 gpm (0.0011 cfs) under a hydraulic gradient of 1 (Powers et al., 2007).

Vertical sand drains would be suitable for dewatering perched water tables or shallow water-bearing units where it would be inefficient to install a pumping well, or where it is desirable to intercept water in a shallower unit that is in direct hydraulic connection with a recharge source before it reaches the area around an excavation. The intervening low-conductivity unit may be cased off or left in connection with the filter material in the sand drain.

Vertical sand drains would not be appropriate where concerns exist regarding interconnections between different water-bearing units or where State regulations prohibit open pathways between different aquifers.

21.8.6.4 Open Pumping

Open pumping, in the simplest terms, is the removal of standing or pooling water from an excavation (figure 21.8.6.4-1) regardless of the source. Some of the most common sources at construction sites could include precipitation, water used in curing concrete, leaking water lines (utilities, WR&C discharge lines, supply lines), equipment wash down or decontamination, and minor seepage from slopes.

Figure 21.8.6.4-1. Unwatering behind a sandbag cofferdam on the Rogue River, Oregon. Cofferdam consists of flexible intermediate bulk containers (FIBC) (also called big bags, bulk bags, or jumbo bags) filled with local sands and soils. Open pumping is removing standing water in a number of pools of various sizes and depths (Savage Rapids Dam Removal and Replacement Pumping Facilities, Grant Pass Project, Oregon, photo by Reclamation Yakima Office staff).

Ditches, drains, and sumps are a form of open pumping. Open pumping can also be as temporary, simple, and "spur of the moment"[18] as a trash pump placed in a depression after a rainstorm. As succinctly put by Powers et al. (2007) ". . . open pumping . . . is not the sort of thing that one can learn from a book; it is learned down in the mud, preferably while equipped with boots of some height."

Open pumping cannot be planned ahead of time; rather, it has to take place as conditions change and the need arises. Thus, the specialist needs to recognize that

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[18] As used here, 'spur of the moment' refers to an action taken in response to a sudden, unanticipated event or condition on an 'as needed' basis.

open pumping will likely be required and be aware of potential open pumping needs as the work progresses. “Every excavation has its own personality and requires specific techniques. The dewatering engineer must be prepared to deal with a variety of conditions.” (Powers et al., 2007, section 17.1)

21.8.6.5 Well Points

In addition to being suitable for shallow dewatering, well points are also suitable for unwatering applications such as standing water, where the removal of suspended fines is undesirable. Well-point systems have the advantage of being very flexible. For example, the well points can be installed quickly; can be installed where needed; can be installed in a variety of patterns, including randomly; can be installed at various depths; and can have as many or as few well points in the system as needed.

21.8.6.6 Filters

Filters, in and of themselves, are not an unwatering technique; rather, they are an internal erosion control technique. They are beneficial when combined with unwatering systems to help control the movement of sediments; in particular, the finer sediments. The variety of materials that can be used as filters is almost as varied as the situations in which they can be used.

- **Geotextiles**: Liners in ditches and drains, linings under poured concrete slabs or engineered ‘filter’ blankets, wrappings around perforated drain pipes, liners inside some drain pipes, and sediment fences along construction site perimeters.

- **Engineered “Filter” Blankets.** Engineered layers of graded, granular filter materials of different sizes along the toes of slopes and on the face of slopes.

- **Sand Filters.** Backfill for trenches and drains, filter blankets at the toe of slopes, and backfill inside vertical sand drains.

- **Straw Bales, fiber Rolls, Sediment Fences.** Sediment barriers and “fences” to filter runoff from construction sites, sediment “barriers” to filter seepage or drainage water before it enters drains or drain pipes.

- **Settlement Ponds.** Although not commonly thought of as a filter, settlement ponds do act as a filter by filtering out suspended sediments in discharge water from the construction site or WR&C operations prior to releasing the discharge water to a stream or recycling it back to the construction site for use in drilling fluids, dust abatement, or other non-potable uses.

Filters are not typically the responsibility of the WR&C specialist, but the specialist can (and should) work with other construction groups in any application where water removal and control are required to design the most effective and efficient project systems.

21.8.6.7 Seals

Seals, like filters, are a water control technique, as opposed to an unwatering technique. Seals are designed to prevent the flow of water in places or conditions where it is undesirable or even detrimental to have flowing water. Also, like filters, seals are generally not the responsibility of the WR&C specialist, except in cases where the seal may be included in the well design.

Seals can often be made more efficient when combined with unwatering techniques. For example, shotcrete on the face of a cut slope is an effective means of preventing seepage from the particular face. By preventing seepage from exiting through the face, there is a risk that water pressures behind the seal will build up enough to break through the seal. Incorporating some sort of drainage behind the seal would help control the buildup of water pressures, thus making the shotcrete seal more effective.

21.8.6.8 Cutoff Walls

Cutoff walls, also referred to as cutoff curtains, are an effective means of stopping or minimizing flows and/or seepage into an excavation when they can be installed down to an impervious layer. Cutoff walls can be made with driven steel or other types of sheet piling, by excavating a trench and backfilling with a slurry of bentonite/soil or soil/grout mixtures, by pressure grouting the existing soils, by in situ mixing of grout and soil, or by secant pile walls and grouting. Like filters and seals, cutoff structures are not the responsibility of the WR&C specialist. However, dewatering and/or unwatering techniques and the cutoff structures are both more efficient and effective when used in combination than when used alone. Refer to *Design Standards No. 13 – Embankment Dams* - Chapter 16, “Cutoff Walls,” (Reclamation, 2015b) for more detailed discussions of cutoff walls.

21.8.7 Design Redundancy

Design redundancy, also called design contingencies or backup systems, is a necessity and is often built into WR&C systems more frequently than in other systems associated with embankment dams. There are many conditions that make design redundancy a highly advisable design criterion. Some examples would be:

1. **Uncertainty in Subsurface Conditions.** Because of the nature of the site conditions, there is never enough design data to identify with 100% certainty every possible variable and property of the subsurface materials. Thus, the WR&C system design must be based on the best available

information, coupled with the specialist's experience and knowledge, in order to account for the majority of conditions most likely to be encountered.

2. **Equipment Malfunction/Interruption of Service.** Equipment malfunction or failure of critical equipment components or interruption of critical services such as power supplies.

3. **Damage/Destruction.** Damage to or destruction of WR&C facilities, components, or operations due to construction activities such as wells being hit or run over by construction equipment and discharge or power lines being cut.

4. **Unexpected Natural Events.** Natural events that are unexpected such as sudden heavy rainstorms, flash flooding, wildfires, lightning strikes and similar natural phenomena that can disrupt or impact WR&C facilities and operations.

Uncertainty of subsurface conditions can often be addressed through a conservative design that would have a built-in redundancy by:

- Slightly oversizing the pumping capacity (individually in specific areas or for the overall system)
- Adding a couple of extra well points to a well-point system
- Deepening wells
- Designing for a greater drawdown than is required
- Oversizing manifold systems and settling ponds, where possible, to maintain gravity flow
- Assuming higher or lower aquifer properties as appropriate
- Having equipment and components to install extra deep wells or well points either on hand at the construction site or capable of being mobilized to the construction site within a reasonable time period. The more the component's failure would impact construction activities or dam safety, the shorter the time period allowed for transportation to the construction site.

Malfunctions or failure of critical equipment components or interruptions of critical services are probably the most common events that will impact WR&C operations. Along with damage to or destruction of WR&C facilities, components, or operations due to construction activities, these conditions are the easiest to plan for, and the plans and preparations are essentially the same.

- Maintain an adequate supply of replacement or backup components onsite (or in a secure, readily accessible offsite location), and in proper working order that can be installed on short notice to replace damaged or malfunctioning components. This would include, but not be limited to: discharge hoses and fittings; flow meters; pumps of various sizes including valves, fittings, and associated ancillary parts; electrical cables and electrical control panels; steel surface casing including cement; riser pipe for the pump; all necessary equipment and materials to install deep wells and/or well points; and instrumentation such as pressure transducers, data loggers, flow meters, water level sounding devices, laptop computer, data cables, etc.

- Maintain backup generator(s) capable of powering the entire WR&C system onsite and in a standby/ready status. They should be directly wired into the power system to come online automatically in the event of a major power failure (if local line power is available and being used), particularly if the failure of the WR&C system for any significant length of time could or would jeopardize the stability of the excavation or other structures, or put human life at risk. The significant length of time would be determined by how rapidly the excavation will start to flood, as well as how rapidly the flooding would reach a point where the stability of the excavation or other onsite works would be jeopardized. The backup power system should be operated for several hours under operational loads at least weekly.

- Discharge lines, power cables, control cables, instrumentation cables, etc., should be routed to be outside of the excavation activities as much as possible. Where such lines have to be within the excavation or crossing access routes, they must be protected from damage by construction equipment. Typically, for road crossings, the cables are fed through a steel pipe of suitable length and I.D. and then buried under the road. Other options might include installing a bypass at critical junction points, dividing the various systems into separate branches to avoid particularly busy road crossings or construction equipment access routes, or constructing an intermediate containment system upstream of major roads or haul routes with a few hours of flow capacity to ensure that the entire system does not go offline due to an interruption in the discharge line. The determining factor would be the degree of risk involved with a disruption of flows or power (i.e., if a disruption would not pose a risk to the open excavation or stability of the excavation for several hours, alternate routes, bypasses, or temporary containment systems would not be as critical. If, however, a disruption of even a short duration would pose a significant risk to the excavation, stability or safety of the embankment dam, or the safety of personnel (to name just a few potential significant risks), backup systems, bypasses, extra protective measures, and contingency plans are critical design features.

Unexpected natural phenomena are the hardest events to plan or prepare for. Planning and preparing for malfunctions and failures will generally cover natural phenomena as well. The only other thing that can be done is to ensure that all the equipment is as protected as possible at all times and that a plan is in place for extreme emergencies.

21.8.8 Timing Considerations

Many factors beyond the control of the WR&C specialist will impact and even control the design, installation, and operation of the WR&C system(s). Those factors could include:

- Project schedule – milestones, completion dates, etc.
- Construction schedule – amount of time the excavations will be open, what time of year the excavations will be open, and even what construction windows are available during the year
- Excavation design and layout
- Reservoir stage and releases
- Amount, type, and quality of available data
- Project funding and amounts allocated for data collection, design, installation, and operation of WR&C system(s)

Each project is different and unique, and each comes with its own constraints and timelines. There are no hard and fast rules, or even guidelines, as to when the WR&C design process should begin or at what stage in the design process it is absolutely necessary for the WR&C specialist to be onboard the design team; however, the earlier the specialist is brought onboard the team, the better the WR&C design will be in terms of efficiency, effectiveness, and cost.

> *For example: At the same dam as was discussed in sections 21.6.7.3, 21.6.8, and 21.8.5, the dewatering system was installed and tested a full year before construction was scheduled to begin. Because of the presence of an unmapped high-productivity zone under the dam site (discussed in section 21.6.8), if the testing and operation of the dewatering system had not started until several months prior to the scheduled start of construction, either the construction would have been delayed by a year, or the dewatering system would have cost significantly more than it did because there would have been a poorly planned program of installing wells all over the downstream dam site in an attempt to lower the water table ahead of construction while construction was going on.*

> *In this particular case, the WR&C specialist was brought onboard the design team early enough in the design process that a WR&C system could be designed, installed, and tested well in advance of the construction, and the problems encountered could be addressed and resolved in an orderly, stepwise fashion.*

21.8.9 Secondary Groundwater/Seepage Control Systems

Frequently, the dewatering and/or unwatering systems will not control 100% of the groundwater or seepage within an excavation, but the amounts that reach the excavation are so minor that adding additional components to the dewatering or unwatering systems is impractical or not cost effective. In such cases, open pumping or a variety of impervious barriers may be employed alone, or in combination with other components (figure 21.8.9-1), to control the water (refer also to *Design Standards No. 13 – Embankment Dams*, Chapter 13, "Seismic Design Analysis," Reclamation, 2015a). Open pumping was discussed previously in section 21.8.6.4.

Figure 21.8.9-1. Excavation dewatering and unwatering behind soldier pile and sandbag (FIBC) cofferdam on the Rogue River, Oregon (Savage Rapids Dam Removal and Replacement Pumping Facilities, Grant Pass Project, Oregon, photo by Reclamation Yakima Office staff).

Cofferdams, bypasses, and temporary diversion structures are not within the area of responsibility of the WR&C specialist. However, the specialist must consider such facilities when designing the WR&C systems.

If a nearby or adjacent surface water body such as a stream or river, canal, stilling basin, etc., is going to be a constant source of recharge to the groundwater system, it may be more effective and economical to temporarily remove the source by blocking the flow in the surface water feature, rerouting the flow in a stream through a bypass structure or around the worksite, or diverting the flow into a different channel that is farther away from the construction site.

Cofferdams and temporary diversion structures are also useful for collecting runoff or seepage and containing it prior to removing it, particularly where the ponded water cannot be drained away by gravity. Diversion structures are useful for diverting surface flows or runoff away from the work area.

The WR&C specialist should work closely with the project designers to determine the most efficient means of controlling recharge sources, including lowering the reservoir level during construction if possible.

21.8.10 Monitoring and Operational Instrumentation

To ensure that WR&C systems are functioning properly and achieving the objectives of the WR&C program, their operation requires constant monitoring and adjustments. As discussed in more detail in Section 21.10 the key operational parameters that require constant monitoring are:

- Flow/discharge rate from each system
- Flow/discharge rate from each component in a system
- Character of the discharge from each component
- Water levels in pumping wells, observation wells, piezometers, sumps, and trenches
- Power supplies to the WR&C systems
- To a lesser extent, conditions in local recharge sources.

Fortunately, the instrumentation required for this monitoring is not complex or difficult to operate (figure 21.8.10-1) – in fact; most of this monitoring could be done manually. However, in terms of consistency, accuracy, safety, and cost effective monitoring, a combination of analog and automated measuring and recording devices are the preferred means of monitoring the operation and effectiveness of WR&C systems.

Figure 21.8.10-1. Modern data loggers and stand-alone automated transducers and other sensors are very easy to operate by properly trained field personnel (Potawatomi Nation aquifer test, KS, photo by W. Robert Talbot).

Observation wells and piezometers are the primary means of accessing the groundwater regime for purposes of monitoring water levels, and pumping wells are the primary means of monitoring water quality. Pumping wells can also be used to monitor water levels; however, the readings should be viewed with caution because the water level readings in pumping wells are influenced by well parameters such as well efficiency and well turbulence that can result in non-representative water level readings.

The most common instrumentation used for monitoring water levels and water quality, and their applications, are:

1. **Flow Meters.** Many types of flow meters are commonly available, and most are acceptable. Flow meters should be calibrated prior to use, periodically during use, and again after use to ensure accurate readings are obtained and that the calibration has not shifted significantly during operation. Flow meters should have dual measurements: instantaneous flow and cumulative flow. Flow meters should be properly installed per the manufacturer's instructions on the discharge side of each system and, in the case of deep wells, also on the discharge side of the pump (figures 21.8.10-2 and 21.8.10-3).

Figure 21.8.10-2. Totalizer in-line flow meter installed in a straight section of discharge line. Straight sections of pipe are required both upstream and downstream of the flow meter to ensure non-turbulent flow through the meter for accurate readings. Required lengths of straight sections of pipe will vary with meter size and design (Grassy Lakes Dam, Wyoming, photo by W. Robert Talbot).

Figure 21.8.10-3. Totalizer in-line flow meter installed in a straight section of discharge line (closeup view). Straight sections of pipe are required both upstream and downstream of the flow meter to ensure non-turbulent flow through the meter for accurate readings. Upstream length was 2 feet, downstream length was 1 foot because of the low sustained discharge rate obtained during this test. Note the butterfly valve at the end of the pipe section used to control discharge rates (Red Willow Dam, Nebraska, photo by W. Robert Talbot).

Decreasing flow rates from a system or a component of the system can indicate several subsurface conditions: one condition that is desirable and other conditions that are less than desirable. The desirable condition is that the water levels are being drawn down. The less than desirable conditions include:

a. Well screen is clogging or slot size is too small.

b. Filter pack gradation is too fine.

c. Well efficiency is very low.

d. Full or clogged inline sediment trap.

e. Pump has excessive wear (less likely condition).

A clogged or malfunctioning flowmeter can also resemble decreased flow rates. If a flowmeter is suspected of clogging or malfunctioning the discharge rate can be verified using a bucket and stopwatch, a weir, or other means of manually measuring discharge (Reclamation, 1984).

2. **Character of Discharge.** The character of the discharge from each WR&C system, as well as from each component, should be monitored on a periodic basis after the system(s) are put into operation. The primary parameters that should be monitored are color, turbidity, and sanding rate.

    a. **Color Meters or Color Scales**. The color of the discharge can be an indication of a change in water quality such as dissolved minerals, organic decay, and algae growth.

    b. **Turbidity Meter.** Turbidity, like color, is an indicator of water quality; in addition, it is an indicator of very fine-grained suspended sediments in the water.

    c. **Rossum® Sand Tester (or equivalent).** The sanding rate is an indicator of the removal of fine sand-sized particles from the well's filter pack and/or formation.

    All three characteristics should clear up over time and with continued pumping or further development, except the color of the water, which may be an inherent characteristic of the aquifer waters and may never clear up.

    Rarely, site conditions may warrant an initial background water quality test such as known or suspected zones of contamination, poor water quality, potentially harmful internal erosion, etc. If regular monitoring of water color and turbidity indicates deteriorating or changing water quality conditions, subsequent water quality testing may be conducted and compared to the background water quality results to identify the changes and to evaluate the impact(s) to the WR&C system and the construction activities/plans.

Any characteristic that does not clear up or becomes worse could indicate changing conditions in the well or formation and may be a precursor to significant problems in a well or WR&C system. The characteristic of most concern is the sanding rate. Sanding rates that are very high (on the order of 100+ ppm (milligrams per liter) that do not decrease, or actually increase over time, could indicate subsurface conditions similar to piping in surface discharges. Additionally, high sanding rates can reduce a pump's service life from years to months and cause excessive wear in valves, meters, and piping.

3. **Water Level Sounders.** There are many different methods to obtain water level readings in wells and piezometers, from manual analog equipment to automated digital systems. Manual methods can consist of "pop-it"[19] lines, chalked steel tapes[20], electronic water level indicators (figure 21.8.10-4), etc. These methods are the most susceptible to human errors in the readings, and accuracy is generally to within 0.1 foot. They also are the most time consuming methods of measuring and recording water levels. See USGS (2011a, b, c, and d) for procedures on using these manual methods.

   Automated methods to obtain readings consist of some sort of pressure sensor/transducer (figure 21.8.10-5) (sometimes referred to as a piezometer) installed in the well and either self-contained or connected to a recording device such as a data logger and/or laptop computer (figures 21.8.10-6 and 21.8.10-7). These devices are highly accurate (although they also require periodic calibration in the manufacturer's facilities) to within 0.001 pound per square inch (psi). They can obtain and record measurements (readings) at rates of several readings per second down to a reading per day/week/month. In addition, they can store months' or years' worth of readings for later retrieval. Some sensors are self-correcting for barometric pressure changes, while others can store the barometric pressures for later corrections. See USGS (2011e) for procedures on using pressure transducers.

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[19] A 'pop-it' line is a measuring tape with a bell-shaped weight on the end. When the tape is bobbed up and down at the water surface, the bell shaped weight will make a popping noise as it contacts the water surface, thus indicating the depth to the water surface.

[20] Chalked steel tapes use dry chalk rubbed onto the end of the tape, and then the tape is lowered into the well to a specific depth. When the tape is retrieved, the wet chalk on the tape marks the depth to the water surface.

Figure 21.8.10-4. Electronic water level sensor (reprinted with permission from In-Situ Co.).

Figure 21.8.10-5. Examples of dedicated pressure transducers without data cables or vented cables to data logger (reprinted with permission from In-Situ Co.).

Figure 21.8.10-6. In-Situ Hermit 3000® data logger and rugged field laptop. Data logger is connected to dedicated pressure transducers via the yellow, vented cables. Data is downloaded from the data logger to the laptop every 8 hours in case of data logger failure. Light tower is for night-time monitoring of the aquifer test (Red Willow Dam, Nebraska, photo by W. Robert Talbot).

Figure 21.8.10-7. In-Situ Hermit 3000® data logger and “Rite-in-the-Rain” field notebook. Data logger is connected to a dedicated pressure transducer in a pumping well via the yellow, vented cable. Drawdowns are recorded manually every hour, and the corresponding data logger readings are manually recorded in case of data logger or transducer failure (National Desalination Research Facility, Alamogordo, New Mexico, photo by W. Robert Talbot).

Figure 21.8.10-8. Multi-parameter automated probe with interchangeable sensor arrays (reprinted with permission from In-Situ Co.).

In addition to pressure readings, many automated sensors can also obtain readings of other water parameters such as temperature, pH, conductivity, dissolved oxygen, oxidation-reduction potential, and a variety of constituents in the water. Most of the older sensors only record pressure, while the newer sensors typically record pressure and temperature, and the more complex devices will record up to three or four parameters in addition to pressure and temperature using interchangeable sensors.

4. **Power Supply Monitoring.** Power supplies, as well as the pump controls, require constant monitoring to ensure that the WR&C systems remain operational (figure 21.8.10-9). Any break in power or operation of the dewatering system could pose a significant risk to the stability of the excavation and the safety of the construction crews, and it could potentially cause significant delays in the construction schedule.

Figure 21.8.10-9. Typical aquifer test setup. Data logger is connected to pressure transducers in a pumping well and observation wells and is set up near the generator that is powering the submersible pump. This allows the WR&C specialist to monitor the progress of the aquifer test and power supply (Grassy Lake Dam, Wyoming, photo by W. Robert Talbot).

Power supplies can be easily monitored by tying an alarm system into the power supply so that if power fails, the alarm system is activated. At the same time, there could be an automatic relay that would activate the backup power system to take over supplying the WR&C system(s) with operational power.

If stand-alone generators provide the main power supply (where line power is unavailable or unable to supply the needed power) or the backup power supply, this would also include regularly checking the fuel levels for the generators and refilling them.

5. **Local Recharge Sources.** Local recharge sources can be monitored visually or with sensors. In standing water bodies, pressure sensors are adequate to monitor the stage to determine if it is contributing to recharge and, if so, to what extent. In streams or outlet works, gaging stations or weirs are suitable means of monitoring potential recharge (i.e., a loss or gain of flow between an upstream and a downstream measurement point). Additionally, strategically located observation wells or piezometers near the water bodies would be able to monitor for changes in the groundwater gradients near the water body. Changes in groundwater gradients could indicate induced recharge from the water body caused by the well’s zone of influence intersecting the water body.

21.8.11 Specifications and Drawings

For non-negotiated contracts, the WR&C specialist will usually design the WR&C systems. Surface water systems are often designed by the contractor and submitted to Reclamation for approval. However, in non-negotiated contracts, Reclamation’s WR&C specialist may design specific dewatering and/or unwatering components in cooperation with the excavation designers. The plans and specifications should normally contain detailed requirements for dewatering and other drainage control measures during construction. For negotiated contracts, the construction contractor generally designs the water control systems, which are submitted for Reclamation review. The data for design must be furnished in the specifications, if available. Otherwise, the contractor will be required to collect the necessary data, which, in turn, requires an adequate time allowance in the contract to obtain it.

A contractor’s proposal (for dewatering) will not bind them to the system proposed for construction. As such, language in the specification needs to clearly and strongly indicate what must be achieved by the dewatering system before excavation can proceed. Written specifications that allow the contractor to design a dewatering system must be absolutely clear about the objectives of the system, the operational conditions that must be met, and the procedures that must be observed. The specifications must require that a monitoring system be an integral part of the dewatering system, the objectives of monitoring and evaluating the effectiveness of the dewatering system clearly identified the operational conditions that must be met, and the documentation that is required by Reclamation.

21.9 Water Removal and Control: Systems Installation Considerations

21.9.1 General Description

Many factors come into play in the design and installation of any WR&C system, including site conditions (the most important site conditions include geology, access, weather, groundwater conditions, and embankment dam operations), excavation plans, construction schedules, and project goals and objectives.

This section discusses some practical guidelines and considerations related to the installation and testing of the WR&C systems as a whole. While each WR&C system will have its own unique characteristics, many aspects will be common to most systems. Therefore, some practical guidelines apply to most, if not all, system installations. These guidelines are discussed below.

21.9.1.1 Smearing

Smearing is a condition that results when, in the process of drilling a borehole, the fines in the formation are rearranged in a way that clogs the openings between particles. This reduces the permeability of the borehole wall, makes development more difficult, and may reduce the overall effectiveness of the well. While smearing is often a temporary condition that may clear up significantly over the operational life of the WR&C system, it cannot be assumed that it will clear up while the system is operating, which is why adequate development (section 21.9.1.3) is critical to obtaining an effective and efficient well. Some drill methods are more susceptible to smearing than others (see table 21.9.1.1-1).

21.9.1.2 Formation Clogging

Formation clogging results from the use of a drilling mud. Drilling muds are advantageous in certain formations for keeping the borehole open, enhancing the drilling advancement rate, extending the life of the drill bit, and reducing lost circulation of the drilling fluid. Conversely, these advantageous properties of drilling muds also result in the undesirable effect of clogging of the pore spaces, which in very porous formations can extend for a significant distance into the formation. This may impact the development of the well, either by reducing the effectiveness of the development process or extending the time and effort required in development (see table 21.9.1.1-1).

Table 21.9.1.1-1 Table of Advantages and Disadvantages of Different Drilling Methods for Installing Wells and Well Points

Drilling methods			Advantages	Disadvantages
Circulating Fluids (including air)	**Rotary**	Direct Circulation (air or drilling fluids) (figures 21.9.2-3b. and 21.9.2-5)	1. Relatively high penetration rates in most materials. 2. Minimal casing required during drilling. 3. Rig mobilization and demobilization are relatively quick. 4. Well screen is easily installed as part of the casing installation. 5. Minimum of 2-person crew.	1. Rigs may be high maintenance. 2. Access and onsite mobility may be limited. 3. Special procedures required for accurate sample collection. 4. Drilling is difficult and more costly in cold temperatures. 5. Rapid unloading of borehole may cause a blowout. 6. Use of drilling muds may cause clogging of certain types of formations. 6. Additional knowledge and experience are required for drilling fluid management.
		Reverse Circulation (figures 21.9.2-3b and 21.9.2-5)	1. Minimum disturbance of porosity and permeability in immediately adjacent bore hole materials. 2. Large-diameter boreholes are relatively quick and economical to drill. 3. Casing is not required during drilling. 4. Well screen is easily installed as part of the casing installation. 5. Suitable for most materials except igneous and metamorphic formations. 6. High penetration rates in unconsolidated materials. 7. Less drilling mud additives are used, and development is easier and quicker.	1. Requires a large water supply. 2. Rigs are larger and more expensive. 3. Large mud pits are required. 4. Large rig sizes limit onsite mobility and access to some sites. 5. Extra cost for drill pipe, air compressors, and special rig attachments. 6. Drill pipe handling times increase with borehole depths. 7. Larger crews are required (compared to other methods).
		Casing Advancement	1. Well suited for unconsolidated formations. 2. Borehole is stabilized during entire drilling operation. 3. Penetration rates can be rapid. 4. Problems with lost circulation are eliminated. 5. Accurate formation and water samples are possible.	1. Equipment is more expensive than most other methods. 2. Clays, heaving clays, or other sticky materials can limit borehole depth. 3. Noisier than other methods.
		Dual-Wall Air Rotary	1. High penetration rates possible in coarse alluvium or broken, fissured rock. 2. Washout zones are reduced or eliminated. 3. Continuous formation and water samples are possible. 4. Estimates of formation yields can be obtained while drilling. 5. Conventional casing/screen strings can be installed.	1. Drill rig and equipment are costly. 2. Drill crews require specialized training. 3. Limited to holes under 10 inches in diameter. 4. Depths of holes limited to 1,400 ft in alluvial materials and 1,900 ft in hard rock formations.

Table 21.9.1.1-1 Table of Advantages and Disadvantages of Different Drilling Methods for Installing Wells and Well Points

Drilling methods			Advantages	Disadvantages
Non-Circulating Fluids or No Fluids	Non-Rotary	Cable Tool (figure 21.9.2-4)	1. Rigs are generally inexpensive, require minimal maintenance, and have low energy requirements to operate. 2. Rigs have very few access or site condition limitations. 3. Borehole is stabilized during entire drilling operation. 4. Holes can be drilled with air or minimal amounts of water. 5. Accurately located formation samples are possible over entire depth of the borehole. 6. Water levels in the well can be obtained at any point in the borehole while drilling.	1. Penetration rates are slow. 2. Larger diameter or heavier casing wall thickness may be required, so casing costs may be high. 3. Specialized equipment may be required to retrieve long strings of casing in some conditions.
		Bucket-Auger (figures 21.9.2-8, 21.9.2-1, and 21.9.2-2)	1. Suitable for large diameter wells. 2. Casing/screen strings can be installed inside hollow-stem augers.	1. Limited to depths of about 100 feet. 2. Suitable only for unconsolidated sediments without large cobbles or boulders. 3. Causes the greatest degree of smearing.
		Pressure Jetting (figure 21.9.2-7)	1. Produce clean bore hole walls and the most efficient wells; virtually no smearing or clogging. 2. Suitable for unconsolidated materials up to small cobble sizes and soft to moderately soft clays. 3. Suitable for installing many closely spaced wells. 4. Can be used to install wells up to 24 inches in diameter.	1. Use large quantities of nonrecirculated water. 2. Require pressures of up to 300 psi. 3. Can temporarily flood the worksite. 4. Limited to depths of around 120 feet.
		Direct Push (figure 21.9.2-2)	1. Quick and economical. 2. Equipment is small and light weight. 3. Suitable for loose to medium dense sands and soft to medium-stiff clays.	1. Wells limited to less than 2 inches in diameter. 2. Depths limited to reactive weight of equipment. 3. May cause smearing of finer materials over lower, coarser materials.

21.9.1.3 Development

Development is the process of repairing damage to the water-bearing formation(s) resulting from drilling and increasing the porosity and permeability of the formation materials in the water-bearing or production zones immediately surrounding the well (figure 21.8.5-4). This is accomplished by agitating the materials in the production zones (or zones adjacent to the screened interval). The agitation will remove the effects of smearing and formation clogging by moving the finer materials into the well, where they can then be removed. Agitation also has the added benefit of breaking down bridging in artificial filter packs and compacting the filter pack.

The more vigorous the agitation is, and the longer it is focused in a specific zone or interval in the well, the more fines are removed and the further into the formation the effects of development will extend. The development process also includes the removal of accumulated fines following the development of the water bearing zones. This is usually accomplished by pumping or bailing the well’s sump.

There are two general types of development: artificial development and natural development. In both cases, development refers to the material being developed immediately adjacent to the well screen, not the methods of agitating the materials. Artificial development refers to developing an artificial filter pack around the well. The artificial filter pack is a graded granular material placed in the annular space between the well screen and the borehole wall. Natural development refers to developing a natural filter pack where the native materials in the borehole are allowed to cave in around the screen to form a filter pack.

21.9.1.4 Operations

How the WR&C system(s) will be operated will impact the design and, hence, the installation of the system components. If, for example, a pumping well or an observation well is going to be destroyed during construction, low-cost materials might be used, such as polyvinyl chloride (PVC) instead of steel. Likewise, a lot of effort may not be put into development.

If a component is going to be used several times, which is often the case with well points, higher-cost, long-lasting materials should be used.

Typically, the initial flow rates from wells and well points during dewatering are higher than the flow rates after the dewatering objectives have been attained and the WR&C system is simply maintaining dewatered conditions. In such cases, the pumps installed in wells and the well point suction pumps must be capable of operating effectively under both flow rates, or they must be switched out at some point in the operations.

Not all wells or well points will be operating continuously; some may only need to be operated intermittently to maintain dewatered conditions. Such cases will require a different type of pump or a different control system to cycle the pumps on and off as needed.

21.9.1.5 Effectiveness

The goal of any WR&C system is to be the most effective system possible (both in terms of operational effectiveness and cost effectiveness). A well-designed and properly installed WR&C system will be the most operationally effective system, which, in turn, will be less costly to operate in terms of number of components, maintenance, replacement, and operational durations.

The perfect system ideally will have the exact number of necessary components that will operate at 100% efficiency, no component will fail or be damaged during operation, and the groundwater system will respond exactly as anticipated. However, the perfect system is unattainable simply because a complete knowledge of every facet of the groundwater system would be required to estimate precisely how the groundwater system will respond. In addition, equipment fails, accidents happen, and rarely do human-designed systems perform precisely as designed. Thus, a built-in redundancy (section 21.8.7) is necessary to ensure adaptability to changing or unexpected conditions and to compensate for the inherent deficiencies in system effectiveness.

21.9.2 Installation Equipment

Installation equipment for WR&C systems is as varied as the systems themselves, and the equipment used depends on the type of WR&C system installed, local geology/soil conditions, size of the system components, method of installation, time available to install the system, available site access, and budget.

Installation equipment can consist of everything from a hand shovel to a multi-ton, large diameter, deep capacity drilling rig. The type of WR&C component being installed should determine which types of equipment will be used during installation. However, it is often based instead on the type of equipment the WR&C contractor has available. Most modern drill rigs can perform two or more installation methods, while some methods are mutually exclusive. For example, a drill rig that is designed for rotary equipment will not be able to employ cable equipment.

The typical installation methods include (table 21.9.1.1-1):

- Rotary methods
    - Air rotary
    - Mud rotary

  - Reverse mud rotary
  - Auger stem rotary
  - Hollow-stem auger rotary

- Non-rotary methods:
  - Cable tool
  - Bucket auger
  - Pressure jetting
  - Direct push
  - Excavator or other excavation equipment
  - Hand dug

Each type of WR&C system has a typical assortment of commonly used equipment, and there is some overlap between system types, which makes some of them suitable for installing a variety of WR&C components. The commonly used equipment, by system type or component, are:

- **Deep Wells, Jet-Eductor Well Points, Observation Wells, Piezometers, and Relief Wells**. The depths and sizes of the wells determine which type of equipment is used. The installation of deep wells and deep eductor well points will require a drill rig of an appropriate size (figures 21.9.2-1 through 21.9.2.5), along with the usual support vehicles, as opposed to a smaller sized rig.

  - **Pipe Truck.** A flatbed truck used to haul extra drill stems, well casing, and well screen. It may also haul filter pack materials, cement, bentonite sealing materials, water tank, etc. (figure 21.9.2-6a.).

  - **Support Truck.** A truck used to carry tools and spare parts. It is usually used by the drill crew to travel between the drill site and lodging (figure 21.9.2-6b.).

  - **Water Truck (or tanker truck).** A truck used to supply water for drilling fluids if a local water source is unavailable.

  - **Ancillary Vehicles.** While not directly involved in the drilling and installation process, a bulldozer may be needed to level off a drill pad for the drill rig and its support vehicles, to construct an access route to the drill site, and to construct a mud pit, settling basin, and associated earth movement. An excavator or similar piece of equipment may also be used to construct mud pits and settling basins.

- **Well Points and Shallow Eductor Well Points.** The depths of the well points and material that the well points are installed in will determine the equipment used. The four common methods of installing well points are:

Figure 21.9.2-1. Continuous-flight auger mounted on an all-terrain carrier (figure 2-22 in Reclamation, 1990a).

(a) Pickup mounted

(b) GeoProbe® track mounted

Figure 21.9.2-2. Examples of other small diameter rigs: (a) pickup mounted, and (b) GeoProbe® track mounted rig (photo credits: (a) unknown, (b) Roger Burnett, Reclamation). Wells can be drilled, augered, or direct pushed.

(a) Trailer-mounted rig

(b) 2-ton flatbed rig

Figure 21.9.2-3. Examples of larger diameter (up to 8-inch wells) rigs capable of depths to 300 feet: (a) trailer mounted rig, (b) Reclamation Upper Colorado Region drill rig (photos by W. Robert Talbot).

Figure 21.9.2-4. State-of-the-art cable tool rig, circa 1935 (reprinted with permission from Johnson Screens, Inc.).

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Figure 21.9.2-5. Upper Colorado Region drill crew's Gus Pech 3000 CHR top head rotary rig; 30,000 torque, 32,600 pounds pull back (photo by Scott Jensen, Reclamation's Upper Colorado drill crew, A.V. Watkins Dam, 2011).

(a) Crane truck support vehicle

(b) Crew truck support vehicle

Figure 21.9.2-6. Examples of support vehicles: (a) crane truck used to carry drill pipe, well casing and screens, portable generators, welding equipment, etc., often used also to install and remove pumps; and (b) crew vehicle used to transport crew to jobsite, carry fuel for generators, and carry tools and spare parts (photos by W. Robert Talbot). Both vehicles are part of Reclamation's Upper Colorado drill crew.

- **Driven.** Well points are driven (pounded) into the soil; the driving force can be manual (using a post hammer) or mechanical (using stand-alone pulley-hammer assembly or a truck-mounted pulley-hammer assembly). A special drive well point with a hardened steel drive tip is used and steel or galvanized steel column pipe sections are coupled to the drive screen as the well point is advanced. Suitable in loose, fine-grained soils with few or no gravel or cobbles.

- **Pushed.** Well points are pushed into the soil using a truck-mounted ram, similar to the way geotechnical probes are pushed. Suitable in loose, fine-grained soils with few or no gravel or cobbles.

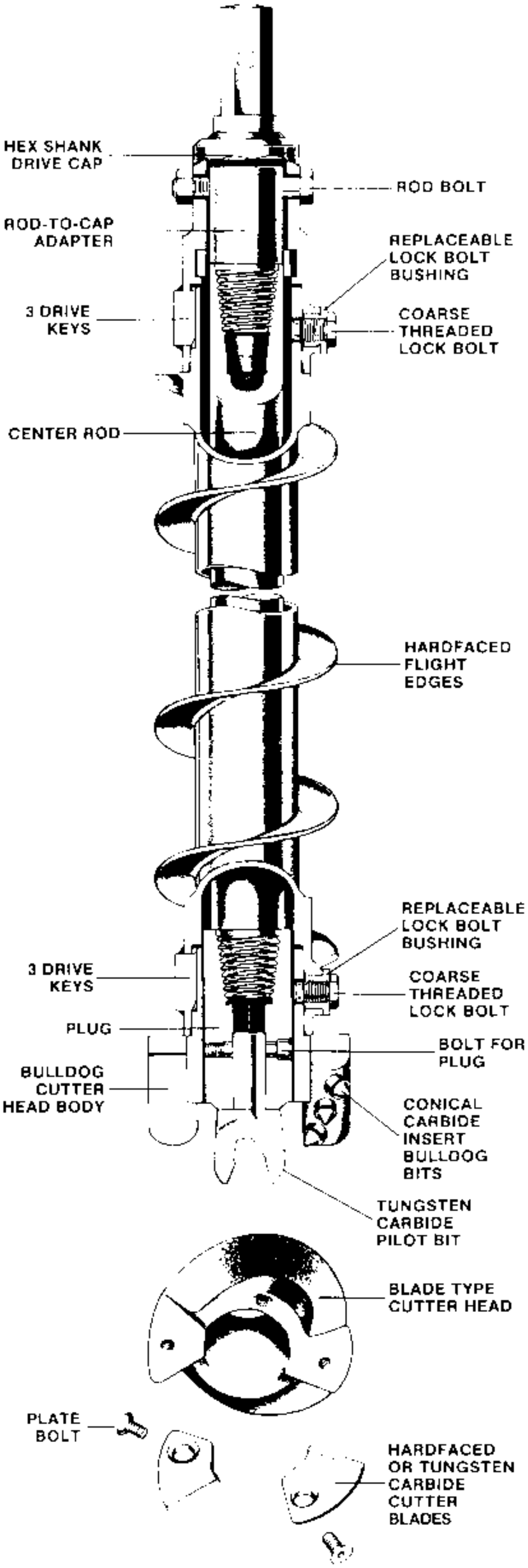
- **Jetted.** Well points are jetted into the ground (figure 21.9.2-7a and 7b) using high-pressure water ejected through special well point tips. Well point is advanced as the soil ahead of it is flushed away. Suitable in fine-grained soils with some gravel or cobbles.

(a)

(b)

Figure 21.9.2-7. Jetted well point installation, manual method: (a) Note overhead power lines that made jetting by a drill rig infeasible (photo by unknown); (b) jetting an eductor well (photo by unknown).

- **Drilled**. Well points are installed in a drilled borehole and are typically drilled using an auger bit (figure 21.9.2-8a and b). Well points can be completed with a filter pack and seals.



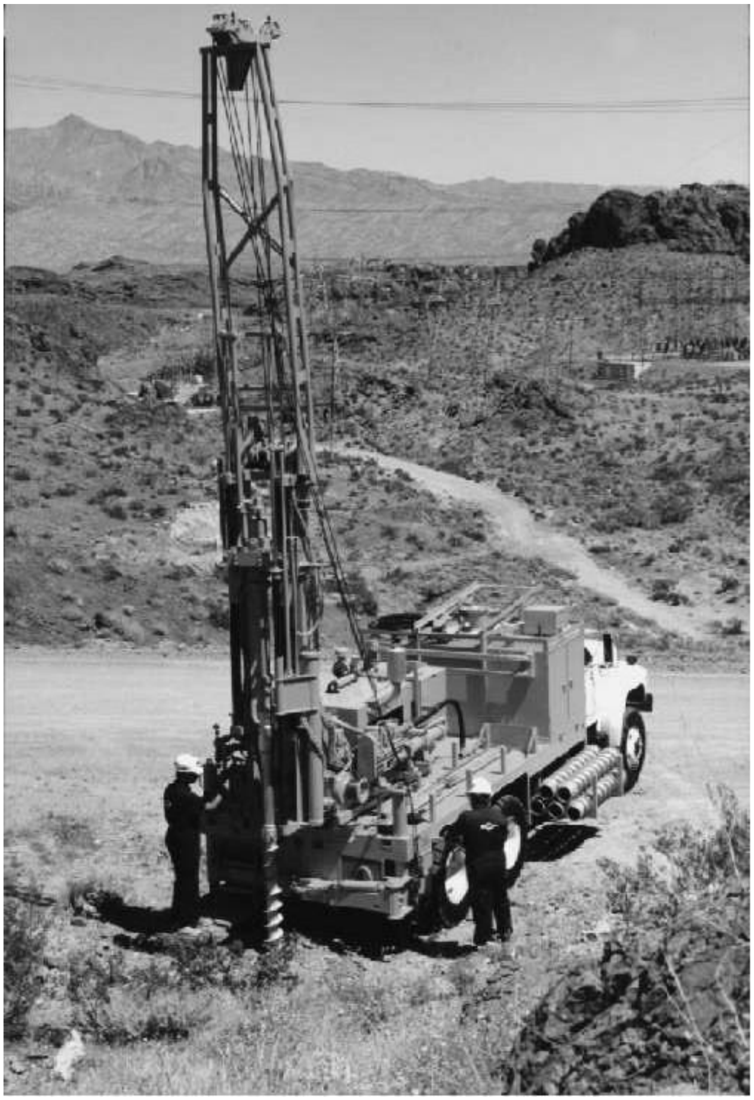


Figure 21.9.2-8. (a) Left: Hollow-stem auger with center plug (figure 2-23 in Reclamation, 1990a); (b) Above: Photograph of typical rotary drill showing some of the essential equipment (figure 2-28 in Reclamation, 1990a).

- **Vertical Sand Drains.** The depths and diameters of the vertical sand drains are the determining factors for selecting the type of equipment that will be used. Typical installation equipment consists of:
    - Jetted Drains. For shallow systems, simply jetting a borehole through a fine-grained unit to connect upper and lower high permeability units is often sufficient, particularly if the material from the upper unit collapses into the borehole.
    - Drilled Drains. For deeper systems, a drilled borehole is an effective means of establishing a connection between two high permeability units by allowing the upper unit to collapse into the borehole.
    - Cased and Packed Drains. Where the materials of the confining unit are not competent, or the upper unit has a significant percentage of fines, then a casing can be advanced along with the jetting tool or drill to keep the borehole open, and the hole is packed with a clean filter sand before the casing is withdrawn.
- **Ditches, Drains, and Sumps.** These are typically surface features and can be constructed manually with a shovel for very small, temporary drainage needs. The use of an excavator would be appropriate for larger areas and/or for larger flows anticipated to last for a significant portion of the time that the excavation is open.
- **Open Pumping.** By definition, open pumping does not require any excavation, per se; rather, it mostly consists of placing a trash pump or similar type of pump in a pool of accumulated standing surface water and then removing the pump after the pool has been drained. This is no more complicated than carrying a pump into the center of the pool, wearing the appropriate waterproof footwear, and running the discharge line to a point that will drain naturally or to an existing sump.
- **Filters, Seals, and Cutoff Walls.** These types of WR&C features are typically outside the responsibility of the WR&C specialist to construct and are beyond the objectives of this chapter (refer to *Design Standards No. 13 - Embankment Dams,* Chapter 16, "Cutoff Walls," Reclamation, 2015b).

21.9.3 Control of Sediment

Sediment control is a critical objective of any WR&C system. WR&C systems that are intended to discharge to a surface water body, such as a stream or lake, will typically require a discharge permit. Most discharge permits have limitations and controls on how much sediment can be discharged to the surface water body. Generally, properly installed deep wells, jet-eductor well points, and traditional well points will have very low sanding rates once they are fully developed. If so, they can often be discharged directly to a surface water body once the final sanding rates have been established. The final sanding rates of dewatering systems can be estimated fairly accurately from the post development testing of individual components of the dewatering system(s), as well as from the overall system testing prior to initiation of site dewatering operations.

However, that is not the case with unwatering systems or dewatering systems that are not properly designed, constructed, and/or developed. These systems may never clean up enough to meet the permit requirements for direct discharge to a surface water body. As such, their discharge will require some sort of treatment before it can be discharged to a surface water body. The most common means of treating discharge that has a high total suspended solids concentration is a settling basin. The basin can be constructed virtually anywhere outside the excavation footprint as long as there is adequate open area for the basin. The basin should be sized to retain 100% of the maximum anticipated discharge from all systems combined for a minimum retention of 1 hour.

The settling basin volume needs to be monitored on a regular basis because as the sediment from the WR&C systems settles out, the volume of the basin will decrease, and the minimum 1-hour retention time may not be met. If that becomes the case, either the discharge from the WR&C systems must be reduced or the basin must be cleaned out (or both).

An alternative to a settling basin is a spreading basin, where an adequate open area and other conditions allow. A spreading basin is a very large, shallow basin to which the discharge waters are routed. The size and bottom materials of the spreading basin allow the discharge water to spread out and either infiltrate back into the ground or evaporate (or both). This would prevent any issues with sediment discharge to a surface water body. The main issue with spreading basins is that they must be located far enough away from the excavation site to prevent the infiltrated water from being drawn back towards the excavation and re-extracted over and over.

Localized sediment control (such as runoff from a construction site, excavated slope, spoil pile, etc.) can be accomplished with the use of bales of straw, tubes of filter media, sand fences, and other means of filtering the sediment out of the runoff before it leaves the construction site (figure 21.8.6.1-1). These materials would be installed on an as-needed, where-needed basis and would be left in place for the duration of the excavation period or only for the duration of a particular precipitation event.

A commonly overlooked source of excess sediment reaching the surface water body is the erosion at the point of discharge, or downstream of the point of discharge caused by the discharge itself. Initially, during the dewatering stage of the WR&C process, the discharge from the dewatering system(s) can reach several hundred cfs to over 1,000 cfs, until the site is dewatered. This can cause significant erosion in a stream or lake where the discharge waters empty into the surface water body. Additionally, a stream that is in equilibrium at flow rates of a few hundred cfs that is suddenly subjected to flows that are double or triple its normal range will experience significant erosion downstream of the discharge site. The discharge points should always be armored or otherwise protected from erosion by discharge water (figure 21.9.3-1), as well as points where surface runoff is being concentrated.

Figure 21.9.3-1. Erosion protection at discharge point. Discharge is reported as 1,000 gpm (Collector Wells International, Inc., 2002, San Ildefonso Pueblo Demonstration Collector Well, Rio Grande, New Mexico).

The WR&C specialist should work with the environmental specialist and a geotechnical engineer to identify appropriate mitigation actions to protect the natural conditions at and downstream of the discharge point.

21.9.4 System Installation

System installation will be controlled by four main factors:

- Specific types or components of the WR&C system(s)
- Construction schedules
- Excavation plans and schedules
- Estimated drawdown time

Because each site and each construction activity are somewhat unique, there are no hard and fast guidelines to system installation. Two of the controlling factors (construction schedules and excavation plans and schedules) have already been discussed in the design of the WR&C system(s).

It is desirable to have the WR&C systems in place, operational, and tested to ensure that they are adequate to achieve the necessary dewatering goals well in advance of the actual excavation and construction activities. However this is not always possible. Factors and conditions may dictate that the WR&C systems precede construction activities and excavation by several months or weeks. In rare cases, conditions (physical, economic, political, or otherwise) may even necessitate that the WR&C system installation be done concurrently with the excavation activities; in even rarer cases, it might be advantageous to do the excavation and WR&C system installation concurrently.

Regardless of when the WR&C system(s) are installed relative to the excavation and construction activities, it is critical that the systems be installed properly, be fully developed, and be operationally tested prior to being brought online.

All wells and piezometers should be fitted with locking covers to prevent debris from entering the well or piezometer, to keep small animals out of the wells, and to prevent vandalism (figures 21.9.4-1 through 21.9.4-4). The well covers should be on the wells and piezometers and locked when the well or piezometer is not being actively used.

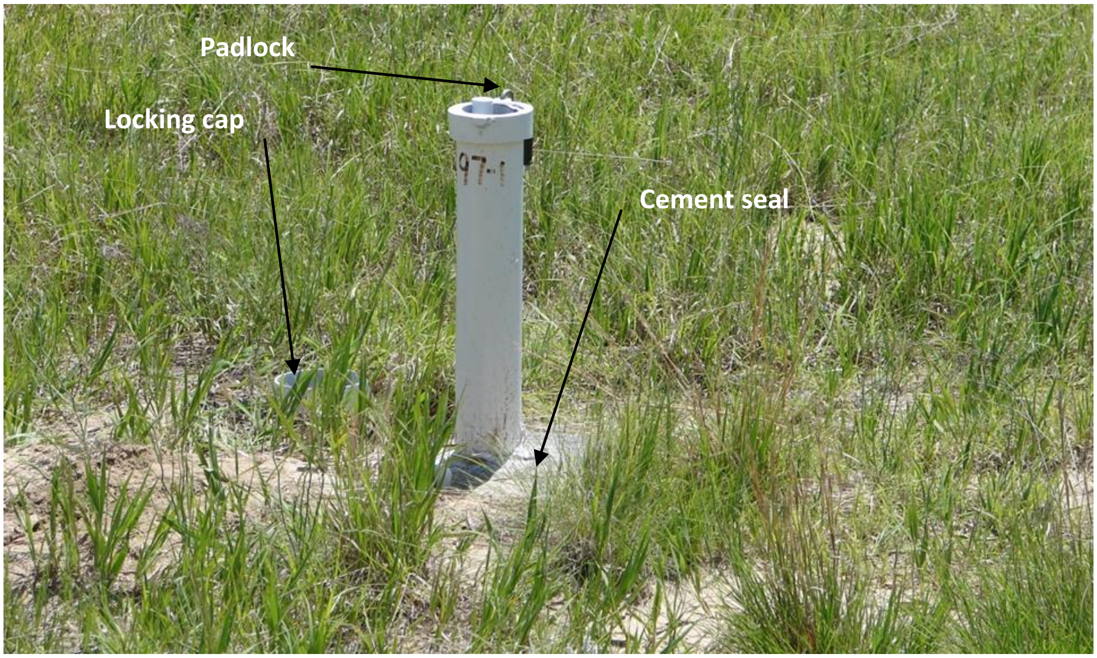


Figure 21.9.4-1. A 6-inch outside diameter steel pipe (painted white) protecting a 2-inch, I.D. PVC observation well. Stick-up (the part of the well and surface casing above the ground) is 2 ft, 6 inches. The steel casing, typically referred to as surface casing, is cemented in the ground and is there mainly to protect the above-ground portion of the PVC casing. The surface casing is different from the well casing that extends above the surface. A locking steel cap has been removed to access the well (photo by W. Robert Talbot).

Figure 21.9.4-2. A line of four observation wells in a field. They are being used to monitor an aquifer test, so all of their locking caps have been removed and temporary pressure probes installed. The depth of the probes are secured in place with loops of extra transducer cabling taped to the top of the well's surface casing as seen on the closest well (the closest well has extra yellow cabling taped to the top of the surface casing with electrical tape (Red Willow Dam, Nebraska, photo by W. Robert Talbot).

Figure 21.9.4-3. Typical above ground portion of a piezometer (photo by W. Robert Talbot).

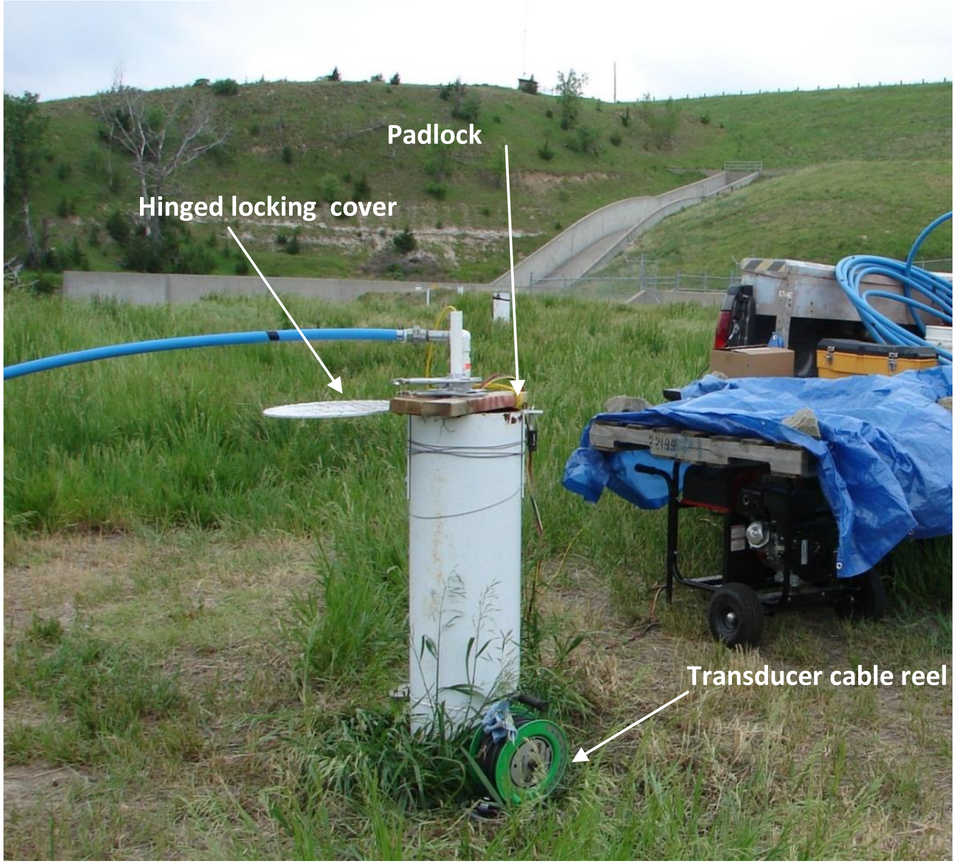


Figure 21.9.4-4 Pumping well setup during an aquifer test (Red Willow Dam, Nebraska, photo by W. Robert Talbot).

21.9.5 Component Testing

There are five steps in the installation of any component of any WR&C system. They are:

1. Component installation: as discussed previously, this step consists of the actual installation of a well, well point, or other component.
2. Component development: as discussed previously, for wells and well points, development is a key step in the installation process. This step establishes the connection between the well or well point and the formation/aquifer/water-bearing materials that ultimately controls the efficiency and effectiveness of that individual component in meeting the goals for which it is installed.
3. Component testing: prior to being connected to other components to form a ‘system’, each component must be tested to ensure that it has been properly installed and fully developed, and is capable of achieving the goals for which it was installed. Testing is primarily used for deep wells (including pressure relief wells and vacuum pressure release wells), jet-eductor well points, and traditional well points. Testing of other types of components such as observation wells, piezometers, sumps, drains, etc. is not as critical as it is for components designed to do the majority of the dewatering duties. Any of the tests previously described can be used to test a given component. If any component should fail any test then the WR&C specialist must decide what actions to take to remediate the component, enhance its ability to perform, or abandon and replace the component.
4. Connection to other components to create a system: having passed the testing, the component is connected to other components to form the intended system.
5. System Testing: at each stage in the construction of a system, as new components are added, the system should be tested under operational conditions to ensure that it still functions as designed. This is discussed more in the following sub-heading.

21.9.6 System Testing

Ideally, every system should be tested under operational conditions prior to being put into service to ensure that the system operates as designed and can meet the objectives for which it was designed. This means that as each component is added to the system, the system is retested. It is better, in a system of 10 interconnected deep wells, for example, to find out that one of them is not developing sufficient head when it is connected to the system than to wait until all

10 wells are connected to find out that one of them has problems. Additionally, this means that the system can be operational and in service before all the components are connected, thus getting a head start on the WR&C process.

System tests generally are not as detailed as individual component tests; rather, they focus more on the integrity and overall operation of the system. As such, the system tests should include verifying that the following conditions are met:

- All the fittings and connections are tight and nonleaking.
- The power system is adequate to handle the startup and operational loads of all the components in the WR&C system(s).
- All the valves and flow meters are functioning properly.
- Each component is capable of pumping against the head pressures in the discharge line.
- Any unique feature or component of the WR&C system is capable of operating as designed when connected to the rest of the system.

When a WR&C system, or any individual component of it, does not operate as designed or expected, the malfunctioning component must be isolated, or the entire system must be shut down until the problem(s) have been corrected. The system should not be placed into service until the malfunctioning component (regardless of the reason) is isolated from the system and/or repaired or replaced.

21.10 Water Removal and Control: Operation and Performance Considerations

21.10.1 Field Observations, Monitoring, and O&M

Constant monitoring of the effectiveness of the WR&C system(s) is a key component to detecting potential problems with the system or changes in the site conditions, and responding to them, before they can become problems.

Once the WR&C system(s) have been installed, tested, and placed into service, continuous monitoring of the system(s) performance is necessary to ensure that it is operating satisfactorily, the goals of the WR&C system(s) are being achieved, and groundwater conditions are being maintained.

System monitoring consists of periodic observations (readings) of the system components, recording the readings, and evaluating the individual readings and trends in the overall observations. The goals of system monitoring are to:

- Ensure that the WR&C system(s) are operating as designed and all components are functioning normally.

- Ensure that the goals of the WR&C system(s) are being met and surface and groundwater conditions are being maintained.

- Identify any changes in the operating conditions, determine the cause(s), and determine if those changes are expected or unusual.

- Identify potential problems with the WR&C system(s), system components, and surface water and/or groundwater conditions so that the potential problems can be mitigated or resolved before they become problems.

To ensure that the goals of the system monitoring are met, the monitoring program should consist of, at a minimum, of the following components/ parts/actions:

- **Observation Schedule.** A schedule of periodic observations of system components and a log (or logs) of the observations, including but not limited to:

    - Water levels in all observation wells and piezometers

    - Water levels in all pumping components (as appropriate)

    - Instantaneous and cumulative flows as indicated by all installed flow meters

    - Pressures in manifold systems

    - Sanding rates of all pumping components (as appropriate)

    - Quality of the system discharge waters (sanding rate, color, odor, turbidity)

- **Maintenance Logs.** A schedule of component maintenance requirements, usually as recommended by the component's manufacturer, and a log documenting component maintenance.

- **Calibration Logs.** A schedule of the manufacturer's recommended calibrations for all components, as appropriate, and a log documenting component calibrations.

- **Inspection Logs.** A schedule of regular visual inspections of pipelines, discharge lines, headers, manifolds, valves, and other fittings for leaks and system integrity.

- **Operational Logs.** Daily activity logs or narratives of events related to the operation of the WR&C system, including but not limited to: (1) power outages and durations; (2) isolation of one or more components for maintenance, repair, or replacement; (3) weather events that would impact water level readings or system operations; (4) summaries of visual inspections and monitoring results; and (5) description of, and results of, site visits by project management, State and/or Federal regulatory agency representatives, and other entities.

Additionally, the monitoring program should include a regular report to project management regarding the operation and status of the WR&C system and noting any changes in trends, component failures, and any other event that is outside normal or expected conditions. Conditions that require immediate corrective actions should be reported to project management immediately.

The frequency of the scheduled observations, maintenance, calibrations, inspections, etc., will depend on several factors:

- Maintenance and calibration schedule requirements should be in accordance with the manufacturer's recommendations.

- Components that do not have manufacturer's recommended maintenance or testing schedules (such as backup generators, standby equipment, etc.) should be tested in accordance with the importance of the component. As an example, backup generators may be a critical component in the event of a power failure of any duration; thus, they should be tested on a more frequent schedule than a standby pump or flow meter.

- At system startup, the drawdowns in the wells and pump flow rates should be monitored at intervals not exceeding 5 minutes until it has been established that the pumps are operating normally and drawdowns are steady.

- During the dewatering phase, pumping rates will be higher and drawdowns will be steadily increasing. However, once the dewatering targets have been achieved and the WR&C system goes from dewatering the site to maintaining dewatered conditions, the flow rates will decrease, the drawdowns will stabilize, and the frequency of obtaining water level readings and flow rates can be reduced (e.g., change from hourly to once per shift).

- Any component for which a failure would pose a high risk to the stability of the excavation, safety of the dam, and/or safety of personnel onsite should be monitored on a schedule commensurate with the level of risk involved.

21.10.2 Discharge Water Control and Environmental Requirements

Control of discharge waters and the environmental considerations were discussed previously in Section 21.9.4. Essentially, every State and local government will have its own permitting requirements for discharge permits, along with its own stipulations as to water quality, protection of the existing environment, and downstream impacts. Every WR&C system should comply with the appropriate State and local permitting requirements. In the absence of State permitting requirements, or in cases where the State does not have jurisdiction, the WR&C system should comply with EPA 402 and 404 permit standards and regulations.

Groundwater does not necessarily have the same chemistry as the surface water it is discharged into. Surface water may contain organisms that may be harmed by groundwater discharge or sediment buildup, either directly from the discharge waters or from erosion caused by the discharge. It is important, therefore, to understand the physical, biological, and chemical environmental impacts of discharging groundwater effluent into a surface water body.

21.10.3 Instrumentation

The types of instrumentation that are typically installed, or could be installed, in WR&C systems were discussed previously in Section 21.8.10. The monitoring program should determine what type of instrumentation should be installed and where it should be installed.

Automated monitoring is best suited for conditions that require accurate readings, a large number of readings in a short period of time (high frequency readings), and/or readings from remote or hard to access locations. Automated monitoring of WR&C systems is usually limited to water level readings and system pressures and flow readings. However, sometimes the collection of temperature data, barometric pressure data, and commonly monitored water quality parameters (such as conductivity [salinity], pH, and total dissolved oxygen can be beneficial for evaluating groundwater conditions. Common causes for changes in groundwater quality parameters in dewatering operations could indicate: (1) a change in the source of recharge waters, (2) a shift in the area being dewatered, (3) a shift in the development of the zone of influence of the dewatering system, (4) the initiation of piping in subsurface materials, or (5) the zone of influence encountering a boundary condition.

Manual monitoring is best suited for visual inspections, low frequency readings, sanding rates, in-line flow meter readings, spot readings, etc. Manual readings are also highly recommended as a backup and check on the automated monitoring system. Manual readings of the automated instrumentation will detect malfunctioning monitoring equipment and will ensure that, in the event of total failure of the automated equipment, some data will still be collected.

21.10.4 Documentation

Documentation is discussed in previous sections where applicable. In general, WR&C system documentation should consist of:

- All field data collected or used in the analysis of existing conditions, including Chain of Custody logs for samples, lab analysis reports, aquifer testing records, etc.
- Model input files, spreadsheets, calculation sheets, and all other means used in the design of the WR&C systems
- Manufacturer's certifications of materials supplied, where specific requirements were needed (such as screen slot sizes, filter pack gradations, casing collapse strengths, pump capacities)
- Manufacturer's warranties, technical specifications, maintenance and calibration instructions and recommendations
- Site Safety Plan and EAP associated with WR&C systems
- Component installation, development, and testing records
- Maintenance logs on all equipment that requires regular maintenance
- Calibration logs on all equipment that requires regular calibration
- Operational logs and monitoring logs
- Copies of all reports submitted to project management, State and/or Federal regulators, permits, and any communications related to the operation, monitoring, and maintenance of the WR&C system(s)
- System Shutdown and System Removal reports

21.10.5 System Shutdown

System shutdown may occur in steps or phases, may be gradual, or may occur all at once. System shutdown may also be intermittent and overlap with system operations (such as where a well-point system has achieved the desired results and is shut down, removed, and reinstalled in a different location).

WR&C systems, or components of the system, may also be shut down intermittently where the yields from any given components are too low for continuous operation of those components to be effective. In such cases, one or more of the system components may be operated on a cycle that will enable them to be shut down periodically and operate only when water levels have recovered to a specified level.

Once the dewatering targets have been reached and the WR&C system is only operating to maintain the target water conditions, some parts of the system may be shut down and disconnected from the rest of the system, shut down intermittently, or controlled by pressure sensors. This will depend on the unique conditions at each site.

Most surface water systems will recover from WR&C activities quite rapidly, while most groundwater systems will recover at a much slower rate. In some situations, it may be desirable, from a construction perspective, to control the rate at which the water systems recover; in this case, the WR&C systems may be shut down in steps or phases.

In general, system shutdown, either in phases or all at once, will be controlled by the construction activities and their requirements to maintain water levels and control of the surface and groundwater conditions. These shutdown procedures should be documented in the operational plans.

21.10.6 System Removal

Upon permanent shutdown, the WR&C system(s) shall be removed and/or abandoned in accordance with EPA, State, or local requirements. Individual components of the WR&C system(s) – such as an individual well, sump, or set of well points - that are no longer needed, even though the overall WR&C system(s) remain operational, shall be removed and/or abandoned in accordance with EPA, State, or local requirements, except that any WR&C component or group of components previously designated as permanent installations shall remain in place and operational.

WR&C system(s) shutdown and removal will vary depending on the type of system installed and the various components installed. In general, unwatering systems and components are typically not designated as permanent systems and can be removed or destroyed.” Pumps, piping, discharge lines, manifolds, and other temporary equipment can be removed. Sumps, trenches, ditches, etc., can be removed and backfilled with appropriate materials and the surfaces can be graded to match the surrounding conditions. Vertical sand drains could be removed and backfilled, if necessary, but they are usually abandoned in place.

Drilled holes that may allow hydraulic communication between two aquifers may need to be abandoned to completely cut off communication. As such, cement grout or cement bentonite may need to be injected or tremied into the hole between the aquifers.

Dewatering systems and/or components of the systems are more likely to be designated as permanent installations than are the unwatering systems and/or components. Typical uses of dewatering systems and/or components that are designated as permanent installations are:

- Deep wells and/or well points kept for long-term dewatering or groundwater control. This determination is based on the requirements of the facility being constructed and will be identified during the design phase of the project. Accordingly, the WR&C specialist will design these particular WR&C system(s) and/or components as permanent installations, not temporary ones.

- Observation wells and/or piezometers kept for inclusion into the dam's monitoring system. During the design phase, the WR&C specialist will work with the instrumentation designers to identify where specific permanent installations are needed, and they can generally incorporate those sites into the WR&C system monitoring plan. The WR&C specialist would then design those wells and/or piezometers as permanent installations, not temporary ones.

Dewatering system well points, because of their shallow depths, should usually be removed instead of abandoned in place. The surface components (pumps, manifolds, discharge lines, etc.) are removed, the well points are pulled, and the holes are backfilled with appropriate materials. Steel well points are easily removed and, in most cases, PVC well points can also be removed. If PVC well points cannot be removed, or State regulations require abandonment in place (of either steel or PVC well points, or both), the surface equipment is removed; the well point is backfilled with cement or a bentonite grout, in accordance with State regulations; the upper 5 feet or so of the well point are removed (broken or cut off); and the site is graded.

WR&C systems consisting of, or that include, deep wells have a similar process for removal or abandonment. Because wells are deeper than typical well points, they are more commonly abandoned in place. Deep wells at embankment dam construction sites are rarely much deeper than 100 feet unless they are installed through the embankment dam. As such, in most wells constructed of steel casing, the casing and screen can be retrieved (pulled). It is often easier and more economical to simply abandon wells constructed of PVC than to pull them; however, it is possible to pull PVC wells depending on how deep the wells are, how they were constructed, and what type of materials they penetrate.

When a well is abandoned, the surface equipment is removed, the pump or other installed equipment is removed, sounding tubes and standpipes are removed, the well is backfilled with cement or a bentonite grout in accordance with State regulations, the upper 5 feet or so of the well or well point are removed (broken or cut off), and the site is graded.

The decision to remove or abandon a well or well point, if not stipulated by State regulations, is often left to the contractor or WR&C subcontractor because any equipment or materials used in the WR&C systems are typically identified as property belonging to the contractor or subcontractor in Reclamation specifications/contracts.

Most States have their own requirements for well abandonment, and all abandoned wells and/or well points must comply with State regulations. In cases where State regulations do not apply, or do not have jurisdiction, at/on Reclamation projects, it is still advisable that well abandonment comply with State regulations to avoid any potential concerns or issues “after the fact.”

21.10.7 Project Closeout Report

Following completion of the construction project, or completion of the WR&C activities associated with the construction project, the WR&C specialist must submit a WR&C Closeout Report for Reclamation’s project files. The report typically contains, at a minimum:

1. All as-built drawings, well logs, and completion reports for wells and/or well points that are designated as permanent installations.
2. Copies of maintenance logs, calibration logs, manufacturer’s specifications, operator’s manuals, and other documentation related to permanently installed components.
3. Abandonment reports for wells and well points that are not designated as permanent installations.
4. A narrative description of the field data collection, design, installation, operation, and shutdown of the WR&C system(s)
5. Data appendices containing:
    a. Field test data.
    b. Installation, development, and testing data for permanently installed components.
    c. Operation data such as water level readings, flow readings, etc.
    d. Pertinent interim reports and communications.

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Appendix A

Geophysical Testing

Appendix A

Geophysical Testing

Geophysical testing to determine aquifer properties (primarily hydraulic conductivity) has been applied and evaluated in numerous studies and at numerous sites around the world. In general, geophysical testing methods only indirectly measure aquifer properties and must be correlated with physical testing methods, both in situ and in a laboratory setting. As such, geophysical testing methods are a tool to be used in conjunction with physical testing methods; they should not be used by themselves without other methods with which to correlate results.

Dewatering project designs at existing or proposed embankment dam sites can use geophysical survey results to improve locations, depths, and spacing of dewatering wells. This is due to the ability of geophysical surveys to provide extensive lateral and depth coverage along profile lines, rather than point location information, as is typically derived from drilling data. Geophysical survey data and drill data in combination can be used to develop a more complete site characterization assessment than is possible with drill data alone.

The literature is full of studies evaluating the usefulness of geophysical testing methods in determining aquifer properties. The use of geophysical testing methods by themselves is tempting, as succinctly stated by Ahmed et al. (1988): “By definition, aquifers are nothing but water-bearing geologic formations and thus geophysics, or rather geophysical prospecting methods, ought to be useful to ground-water investigations.” However, simply locating water-bearing formations is not enough to characterize the aquifer. Aquifer parameters are critical to understanding the groundwater characteristics of an area which, in turn, are necessary to design an effective dewatering system. Geophysical methods are broken down into two primary categories: surface geophysical methods and borehole geophysical methods (see table A-1).

Typical imaging targets for geophysical surveys in dewatering designs include saturated granular soil zones, the top of bedrock configuration, buried channels within bedrock, and the presence of clay layers. Generally, electrical methods and seismic methods are used more frequently than gravity, magnetics, electromagnetics (EM), or ground penetrating radar, although these latter methods may see occasional specialized applications. Among electrical methods, electrical resistivity imaging (ERI; also called DC resistivity) and self-potential (SP) are perhaps the most widely used. Among seismic methods, seismic refraction tomography (SRT) and conventional seismic refraction are the most frequent applications. The following discussions focus on ERI, SRT, and SP as applied to foundation dewatering design issues.

Table A-1. Examples of geologic/hydrologic targets and applicable geophysical methods (modified from Reclamation, 1995)

Geologic/hydrologic target	Geophysical methods	
	Surface methods	Borehole methods
Bedrock configuration	Seismic refraction or reflection, ER, EM; less frequently used are, magnetic, gravity, GPR	N/A
Stratigraphy	Seismic refraction or reflection, ER, EM	Sonic, electrical, or radiation logging; natural gamma, SP
Regional fault patterns	Gravity, magnetic	N/A
Local fracture zones/faults	Seismic reflection, ER, EM, SP	Sonic logging, borehole imaging, SRT
Seepage/groundwater flow	SP	Temperature logging, flow meters
Top of water table	Seismic refraction or reflection, ER, EM	N/A
Porosity of geologic materials	N/A	Sonic, electrical, or radiation logging
Density of geologic materials	Gravity	Radiation logging
Clay content, mapping aquifers and aquicludes	ER, EM	Electrical, natural gamma, or radiation logging
Relative salinity of groundwater	ER, EM	Electrical logging

Note: ER = electrical resistivity, NA = not applicable.

A.1 Surface Geophysical Methods

Surface geophysical methods are usually more suitable for wide investigations and require borehole geophysics and borehole sampling to relate the results to specific subsurface conditions. Surface geophysical methods are not suitable for evaluating or determining the hydraulic conductivity of subsurface materials.

A.1.1 Electrical Resistivity Imaging

ERI is an active geophysical method that measures the electric potential differences at specific locations, while injecting a controlled electric current at other locations (Keller and Frischknech, 1966; Burger, 1992). The theory of the method holds that in an entirely homogeneous half-space, a resistivity value can be calculated for the subsurface by knowing the current injected and then measuring the resulting electric potential at specific locations. However, homogeneity within the subsurface is very rare, and electric current, when introduced, will tend to follow the path of least electrical resistance, concentrating in areas of conductive material and avoiding areas of resistive material.

Figure A-1 illustrates the concept of subsurface electric current flow and how current flow is affected by subsurface heterogeneities.

Ohm's Law describes electric current flow through a resistive material (Eq. A-1). The basic concept of the law relates electric current (I) flowing through a resistor to the voltage (V) applied across the resistor and the conductance of that resistor. The inverse quantity of electrical conductance is electrical resistance (R).

$$\mathrm{R} = \frac{V}{I} \tag{Eq. A-1}$$

It is important to note the difference between electrical **resistance** and **resistivity.** Electrical resistance is not an intrinsic physical material property, but ER is. Electrical resistance, measured in ohms, measures the opposition to the flow of electric current through a defined volume of material. Resistivity, usually defined in ohm-meters, is normalized and measures the difficulty of passing electric current through a material regardless of that material's shape or geometry. This concept may be illustrated by imagining electrical current flowing through a wire. The *resistivity* of the wire would be a specific value determined by the wire's material composition (e.g., copper) and would be the same, regardless of the wire's physical shape. The wire's *resistance* would be dependent on the length and thickness (gauge) of the wire and would change as the wire's geometry changes. Figure A-2 illustrates the difference between resistance and resistivity for a length of wire, as well as the mathematical relationship between the two concepts.

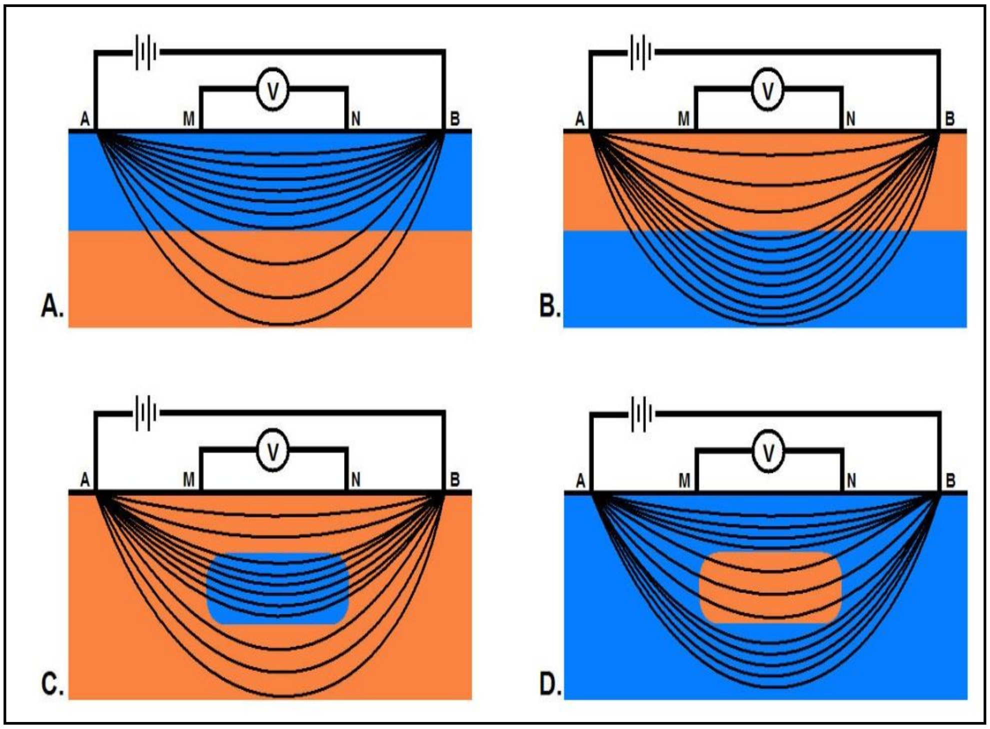


Figure A-1. Variations in subsurface electric current density will occur with variations in earth resistivity. In all images, the blue material is more electrically conductive than the orange material. In image A, the majority of the electrical current flows close to the surface, in the more conductive layer, which leaves very little current flow to penetrate the resistive layer at depth. In image B, the electrical current is drawn to the more conductive layer at depth. In image C, the current flow lines merge to concentrate through the conductive anomaly at the center of the survey. In image D, the current flow lines diverge away from the resistive anomaly at the center of the survey area.

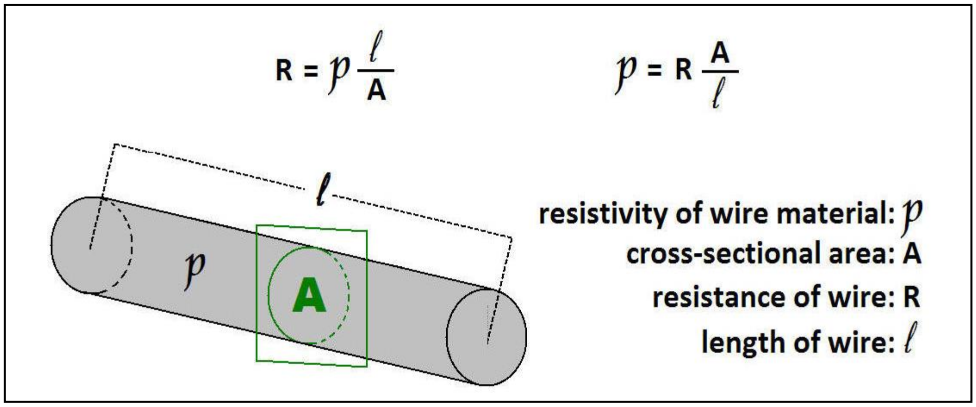


Figure A-2. The relationship between resistance and resistivity.

By substituting resistivity (ρ) into Eq. A-1 for resistance (R), Ohm's Law can be rewritten (Eq. A-2) in a format that takes a material's volume into considerations by defining that volume's cross-sectional area (A) and length (*l*).

$$\boldsymbol{\rho} = \frac{A}{l} * \frac{V}{I} \qquad \text{Eq. A-2}$$

ERI aims to model the ER structure of some volume of the earth. From each ERI measurement, information is gained about the average electrical resistance of a certain volume in the subsurface. Variations in electrical properties of subsurface materials make determination of a true ER model of those materials nearly impossible. Instead, the immediate quantity calculated from an ERI survey is known as apparent resistivity (ρ_a). Apparent resistivity can be thought of as a weighted average of all the true material resistivities in the vicinity of the measurement. Apparent resistivity (ρ_a) is calculated using both current injected and electric potential measured, but it also includes a term that accounts for the relative positions of the current injection and potential measurement electrodes, known as the geometric factor (K). The geometric factor relates resistance and resistivity in a three-dimensional space and can be compared conceptually to the wire's length and gauge in figure A-2. By adapting Ohm's law to account for the conditions specific to ERI surveys, the basic equation of apparent resistivity becomes (Eq. A-3).

$$\rho_a = K\,\frac{V}{I} \qquad \text{Eq. A-3}$$

ERI surveys are sometimes called four-pin resistivity surveys because a minimum of four electrodes are necessary for data acquisition. Two electrodes are used for current injection, and two electrodes are used for measurement of electric potential. The four electrodes can be placed in a variety of configurations, or arrays. Each array has a specific geometric factor. Figure A-3 illustrates the basic formula for determining the geometric factor of any array. By convention, current injection electrodes are referred to as "A" and "B," while potential measurement electrodes are referred to as "M" and "N." Figure A-3 illustrates an arbitrary electrode layout and the resulting geometric factor (K). Most ERI surveys are conducted using one of the conventionally defined electrode arrays. These arrays are typically linear, especially for two-dimensional profiling surveys. The advantages of using consistent and defined arrays are that the resulting geometric factor is simplified and the apparent resistivity calculation for each measurement can be accomplished more efficiently.

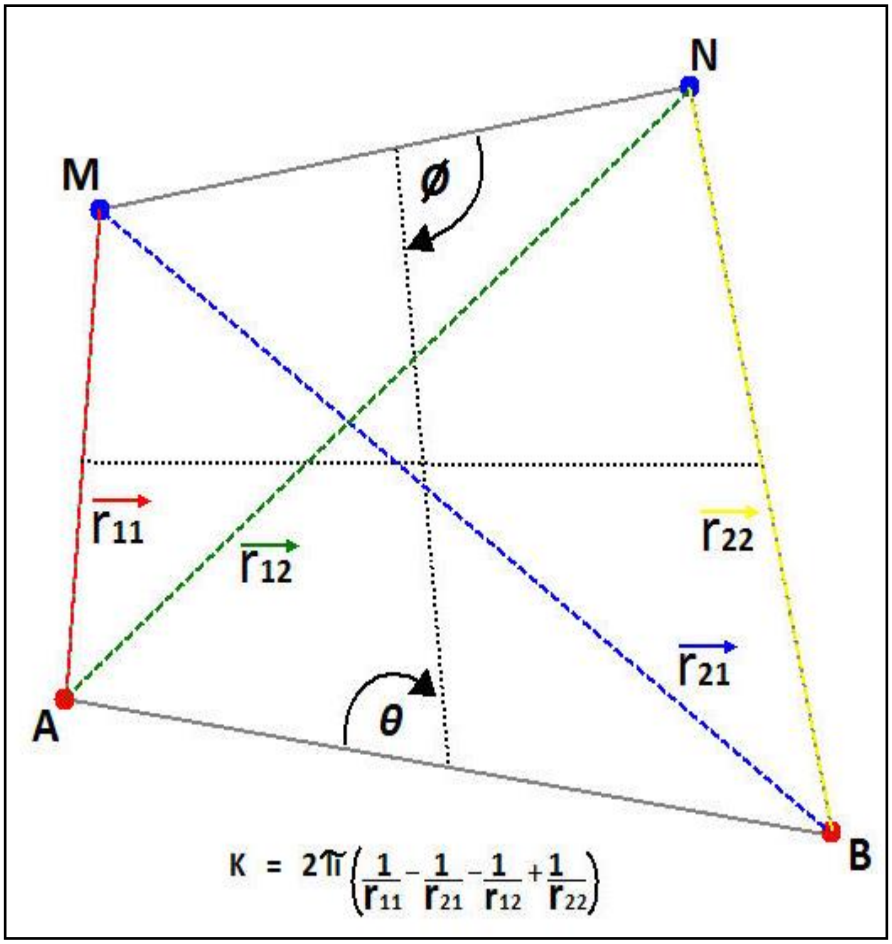


Figure A-3. An illustration of the concept of the geometric factor (K), which is used to calculate apparent resistivity values from measurements of an ERI survey. The geometric factor can be determined for any possible ERI array, as long as the electrode locations are known. Here is an arbitrary layout of two current injection electrodes (red) and two potential measurement electrodes (blue).

A.1.1.1 Resistivity Data Acquisition

For most site characterization studies, two commonly used resistivity arrays are Wenner and Schlumberger. Each array type has its advantages. The Wenner resistivity array provides better depth resolution for a one-dimensional earth, while the Schlumberger array, with its narrower potential electrode spacing, is considered less prone to near-surface lateral changes. It is common practice to test multiple ERI arrays at the beginning of a survey to determine which array has the best resolution for the desired survey target. Figure A-4 illustrates the Wenner and Schlumberger array types and their respective geometric factors.

Figure A-5 shows data from Wenner and Schlumberger array surveys collected over the same profile line. While there are some differences in indicated geoelectric structure at depth, the two surveys show largely the same features.

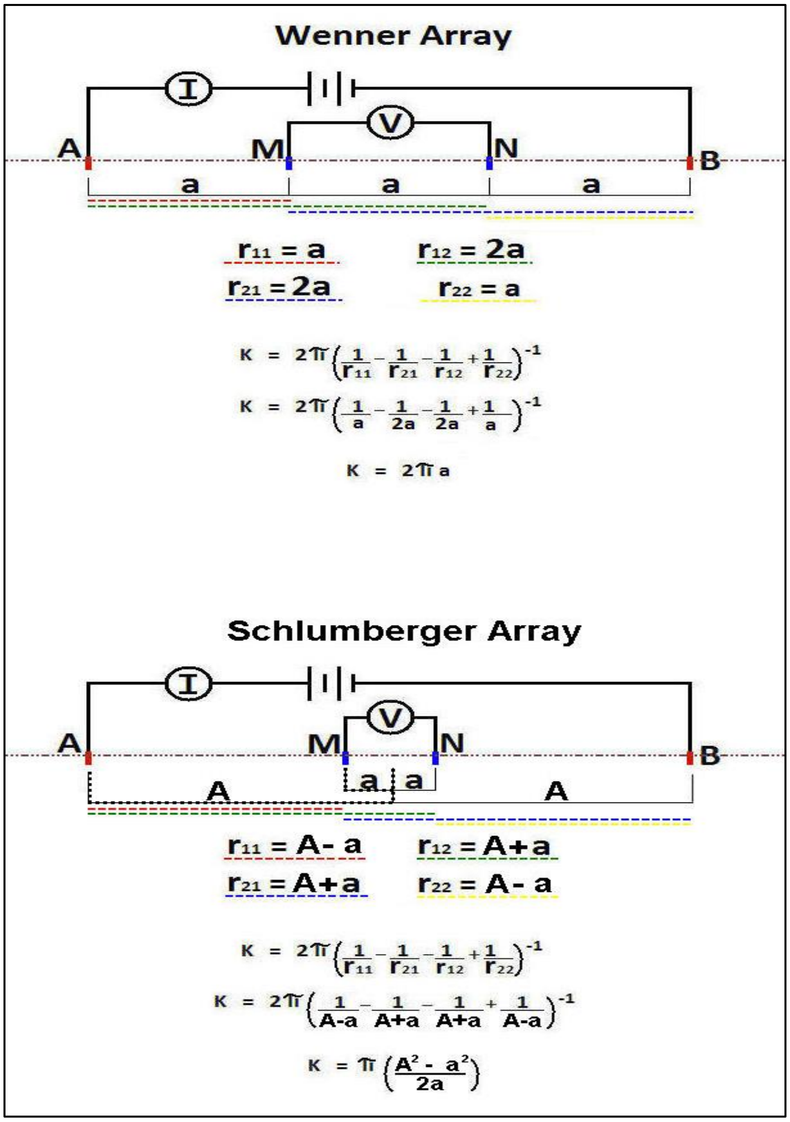


Figure A-4. Wenner and Schlumberger array types showing electrode layout and calculation of the geometric factor for each array.

ERI surveys with commercially available equipment are often conducted by installing a series of 28 to 56 stainless steel electrodes into the ground. The electrodes are commonly 18 inches long and are generally installed to a depth of about 1 foot. The electrodes are connected by means of a cable to a computer-controlled system unit. The control unit is programmed with a script file, which specifies which electrodes are to be used for current injection and which electrodes are used for measurement of electrical potential difference. For any one data measurement, the system only uses 4 of the 56 electrodes. Figure A-6 illustrates instrumentation setup for a typical ERI survey.

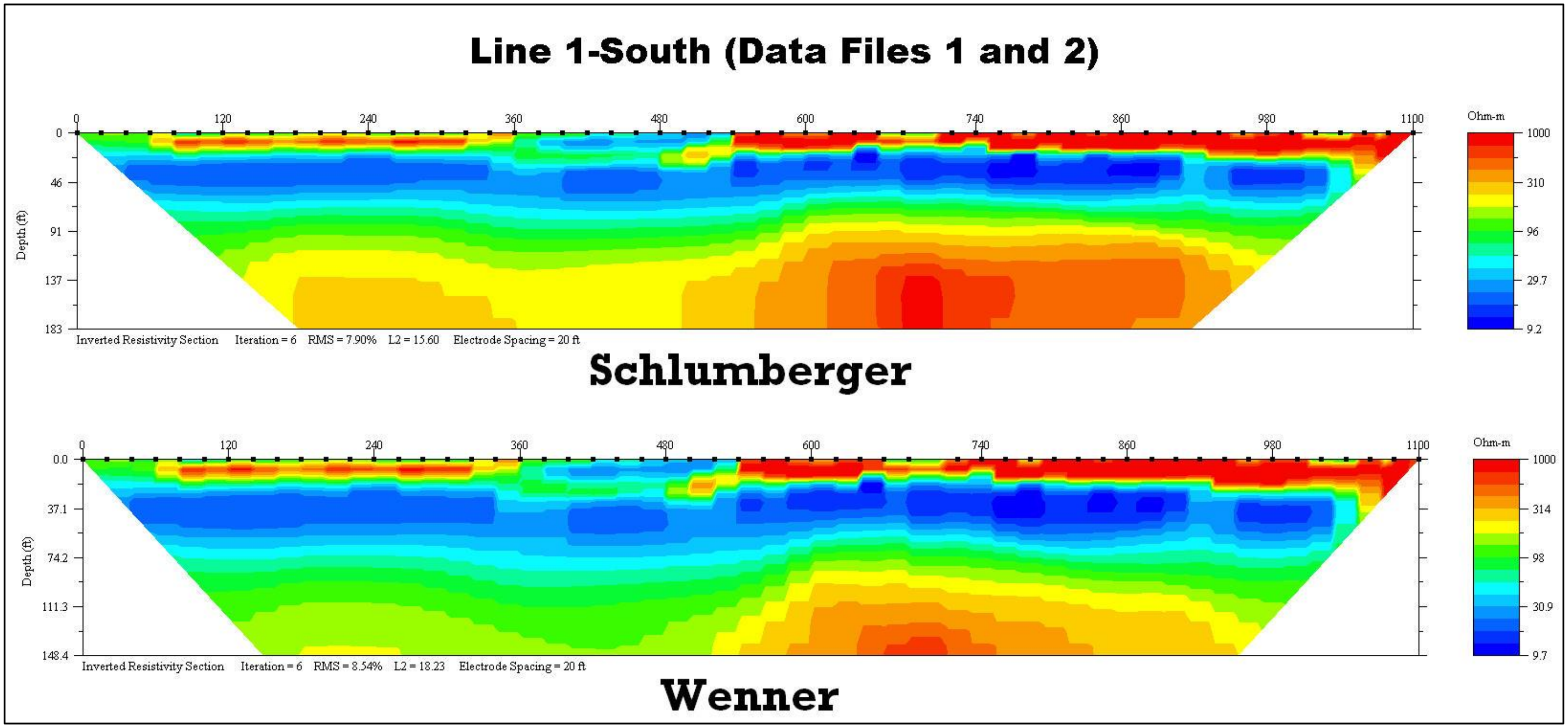


Figure A-5. Field inversions of ERI data collected with two different array types using the same electrode locations. Schlumberger array results are shown in the upper section, while Wenner array results are presented in the lower section. Both array types produced similar subsurface resistivity models, although the Schlumberger appears to show higher resistivities at depth

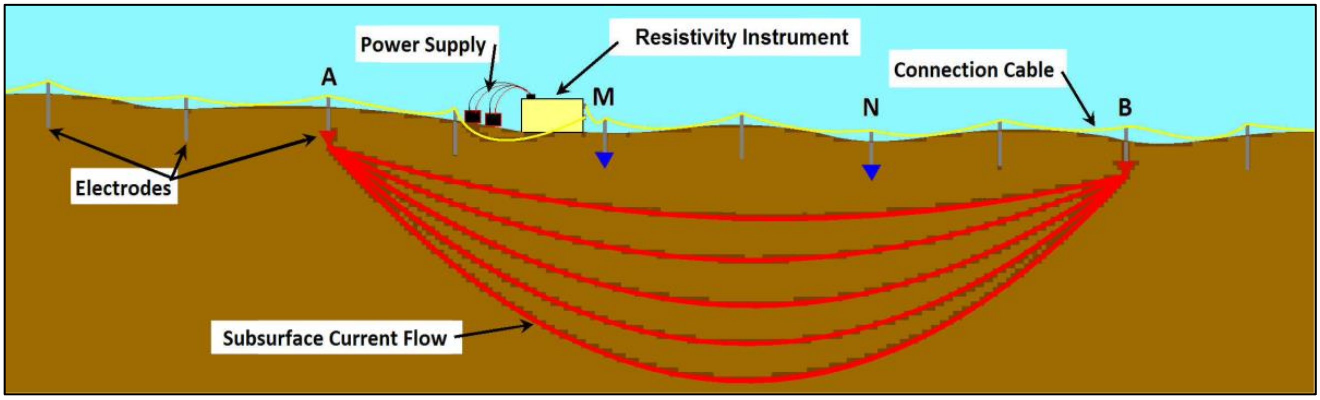


Figure A-6. Conceptual layout of ERI survey array and instrumentation.

A.1.1.2 ERI Data Usage

ERI and SP surveys are commonly run together. Figure A-7 shows results from a combined ERI-SP survey. Electrically conductive zones in the foundation, which may also be observed with changes in the SP profile, are likely candidates for dewatering well locations.

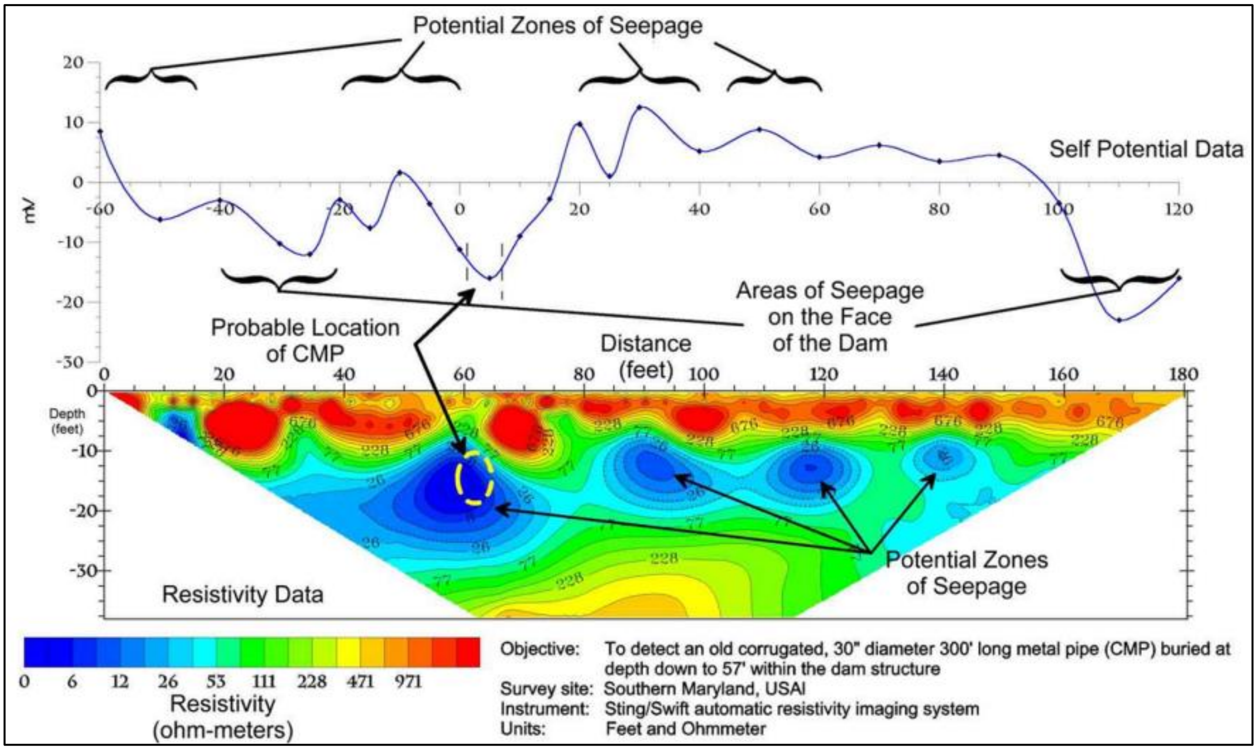


Figure A-7. ER and SP profile results along an embankment toe. Dewatering well location and design can benefit by profile line coverage downstream of the dam toe. (Figure from Advanced Geosciences, Inc.)

A.1.2 Seismic Methods

SRT is a widely used seismic method that has valuable application for dewatering designs. The method relies on the bending (refraction) of seismic wave energy with variations in wave speed, or velocity, through various types of foundation geologic materials. In particular, water saturation of clays and granular materials will cause a marked increase in these materials' compression (p-) wave velocity. This increase is diagnostic in determining the presence and configuration of saturated materials with seismic methods. Additionally, the top of hard bedrock is often observed as another increase in seismic velocity. SRTs then can be used in conjunction with other site information to develop a subsurface picture of the extent and possible saturation conditions of foundation soil materials.

Seismic refraction surveys are used to delineate seismic velocity layering versus depth and distance. Velocities can be compression (p-) or shear (S-), although for dewatering applications, p-wave surveys are more commonly used due to the p-wave velocity's sensitivity to saturation increases. Velocity layering is used to infer which areas are likely to produce water or which zones are likely to represent aquitards, and thereby influence the overall migration of the water at a site. Also, the top of bedrock configuration, and the presence of buried channels within bedrock, are important controlling factors in most dewatering designs.

A.1.2.1 Seismic Data Acquisition

Compression wave seismic sources include sledgehammer sources, weight drop sources, vibratory sources, and explosive sources. Sledgehammer sources use a conventional sledgehammer outfitted with a vibration sensitive switch, which starts the seismic recording system. The sledgehammer is impacted against a metal plate, usually made from aluminum. Sledgehammer surveys are energy limited, being dependent upon the strength of the sledgehammer operator and the level of site background noise. Signal stacking (or summing) is commonly used in sledgehammer surveys. While this adds to the ability of sledgehammer surveys to image deeper at more sites, in practical terms, sledgehammer surveys are usually limited to 0 to 20 feet in reliable depth imaging.

Weight drop sources deliver more energy than sledgehammers, and they typically use an electric motor or other system to raise a weight against a force from elastic bands or springs. Upon receiving a signal from the operator, the weight is released and is accelerated downwards from the force of the elastics or springs.

Weight drop sources are often attached to the towing hitch on a truck or utility vehicle (figure A-8) and are a very efficient way to generate p-wave energy for deep surveys, where a sledgehammer is not sufficient. Depth of investigation for weight drop sources is site and noise dependent but can reach depths of roughly 75 to 100 feet or more.

Figure A-8. Weight drop seismic source mounted on the back of a utility vehicle. The weight drop piston is accelerated by means of large elastic straps, and impacts upon a metal ground plate. (Photo by Rich Markiewicz, Reclamation)

Explosive sources (figure A-9) are required when site characterization must take place to depths of about 100 feet or more. The explosive charges are typically placed in shotholes, which are tamped with sand or other backfill material. A timebreak cable supplies the trigger signal back to the seismic system to start recording. Explosive sources are scalable in that the amount of explosives used is related to the energy imparted to the subsurface. It is generally straightforward task to determine how much explosive charge is needed at a given site. The disadvantages of using explosives include increased safety requirements and enhanced environmental and public safety permitting. Explosive sources are generally not needed for depths commonly encountered in site dewatering projects; however, for very deep investigations, a weight drop source may not have sufficient energy.

Shear (S-) wave sources are generally not used for dewatering site characterization but may be needed for other concurrent site investigations. S-wave sources for small-scale investigations include shear wave planks, purpose-built shear wave cages, and inclined weight drop sources. Shear wave planks are used to generate horizontally polarized S[h] energy. In use, a timber is placed on the ground, and a vehicle is driven on top of the plank with one set of wheels, thereby holding down the plank with roughly half the vehicle weight. A sledgehammer is then used to impact one end of the plank to record shear waves with a specific horizontal polarity. Once the seismic waves from one polarity are recorded, the process is repeated on the other side of the plank for the opposite polarity signal. Purpose-built shear wave cages are similar to planks in that each side of the cage is impacted with a hammer, thereby generating polarized horizontal shear waves. Inclined weight drop sources take advantage of the fact that a weight striking the ground at an angle will generate both p- and S- waves. By inclining the weight to one side and the other, polarized shear waves can be generated.

Figure A-9. Explosive seismic source for SRT survey. (Photo by Rich Markiewicz, Reclamation)

Seismic data are recorded using geophones connected by means of a seismic cable to a recording system (figure A-10a).

The geophones contain a magnet surrounded by a wire coil. The magnet is attached to a steel spike, which is inserted into the ground. When seismic vibrations occur, the spike and magnet both move relative to the coil, and a voltage is created. This voltage is proportional to the vibration movement and is recorded by the seismograph instrument.

Geophones may be used singly or in groups (figure A-10b), with the latter having the advantage of adding signal output from each geophone into a higher voltage signal, while also suppressing noise.

Seismographs used in engineering and groundwater investigations are portable and typically run on 12-volt direct current, so they are usually powered by automotive batteries (figure A-10c). An entire 48-channel seismic system can be carried in a truck or off-road utility vehicle.

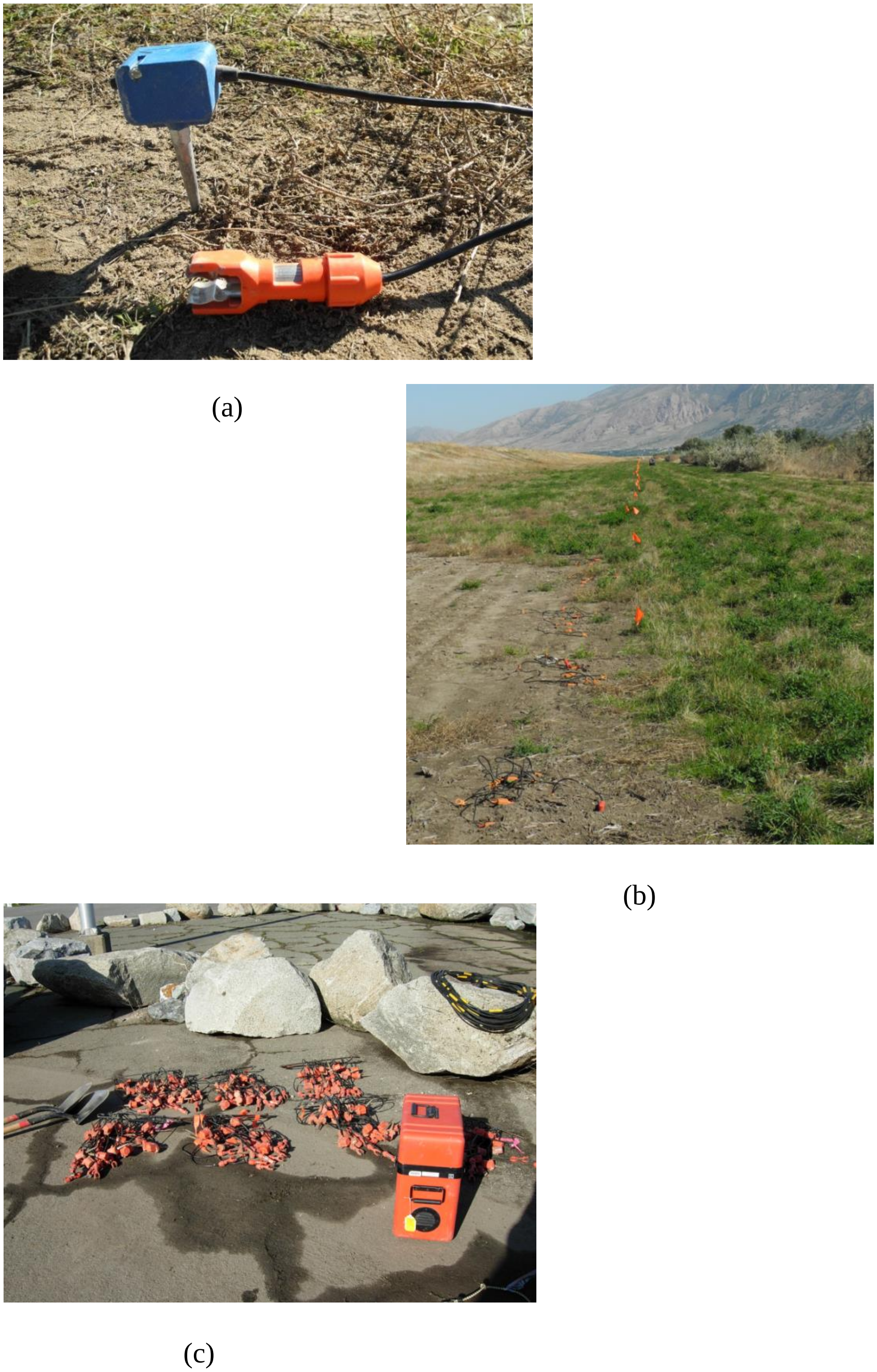


Figure A-10. (a) Geophones connected by means of a seismic cable to a recording system, (b) geophones used in a group, and (c) entire 48-channel seismic system. (Photos by Rich Markiewicz, Reclamation)

A.1.2.2 Seismic Wave Propagation

Seismic p- and S-waves propagate through the subsurface with ray angles described by Snell's Law (Eq. A-4), which specifies how rays will bend with a given seismic velocity contrast, where **i** is the incident angle, **r** is the refracted angle, $\mathbf{V_i}$ is the seismic velocity in the incident (overlying) layer, and $\mathbf{V_r}$ is the velocity in the refracting (underlying) layer.

$$\frac{\sin(i)}{\sin(r)} = \frac{V_i}{V_r} \qquad \text{Eq. A-4}$$

At the so-called critical angle $\mathbf{i_c}$ (Eq. A-5), the refracted angle is 90 degrees, and the seismic wave propagates along the layer boundary. This results in refracted wave energy being detectable at the ground surface as shown in figure A-11.

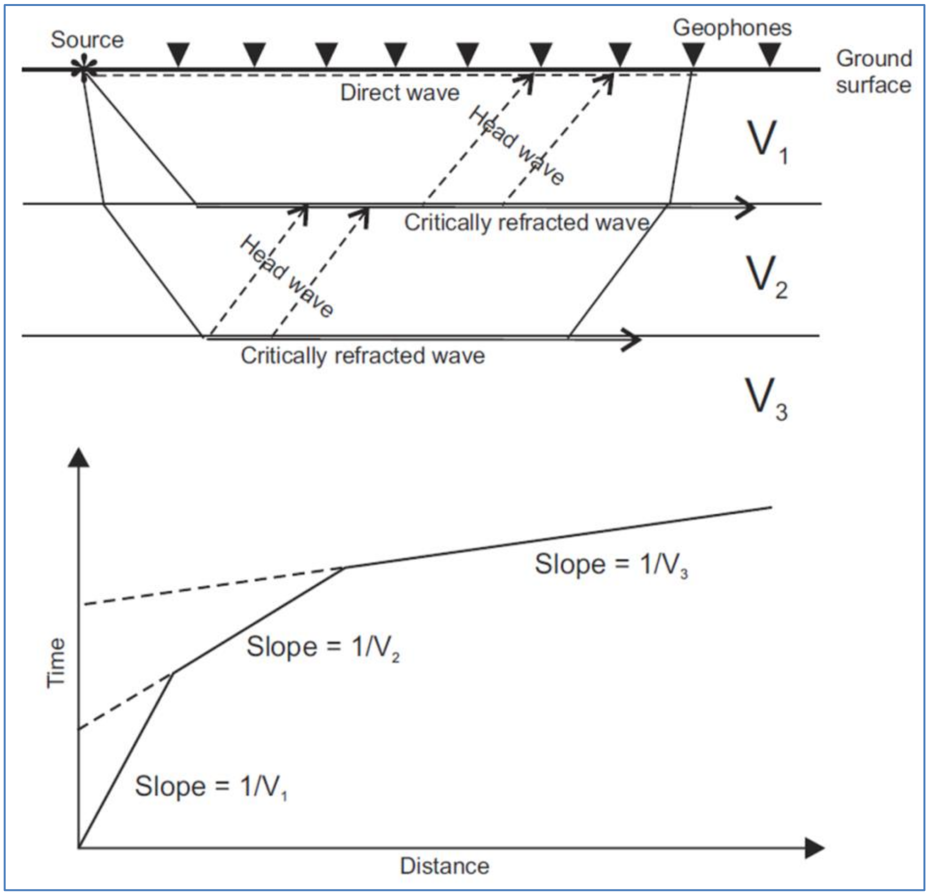


Figure A-11. Seismic refraction ray paths (above) and travel-time curve (below). (Figure from RSK Geophysics, 2012; Hertfordshire, United Kingdom).

$$i_c = \sin^{-1}\frac{V_i}{V_r} \qquad \text{Eq. A-5}$$

Seismic refraction surveys detect these refracted rays, and the data are then analyzed to form a velocity versus depth profile of the subsurface.

A.1.2.3 Seismic Refraction Tomography

SRT is a seismic imaging technique commonly used to delineate locations of top of bedrock, top of saturated soils, locations of various soil type horizons, and possible locations of faulting. SRT can be used with any of the seismic source types discussed above. The results of an SRT survey are generally presented as a diagram of seismic velocity versus depth and profile line distance. The velocities can be either p- or S- wave, depending on what type of seismic source and receivers are used.

For dewatering applications of SRT, unsaturated sands, silts, and gravels will generally indicate p-wave velocities less than about 5,000 feet per second (ft/s) and, more commonly, will be in the range of 2,000 to 3,000 ft/s. With increasing depth, these same soil units may contain close to 100-percent, pore fluid saturation, at which point the p-wave velocity will increase abruptly to 5,000 to 6,000 ft/s, depending on the grain size composition of the soils. Saturated gravels will exhibit higher p-wave velocities than saturated sands or silts.

Clay units may show a more gradational change in velocity because clays are less permeable than granular soils, and they show more lag in pore saturation versus change in phreatic surface elevation. A unit “submerged” by a recent increase in phreatic surface elevation may exhibit a velocity more characteristic of an unsaturated unit, simply because it takes longer for that clay to become fully saturated versus a granular soil layer. Note that pore saturations below about 90 to 95-pecent water will appear to the p-wave survey as “unsaturated” because the compression wave effect is able to compress the pore gas.

The converse of the case mentioned above would be where pumping has reduced phreatic surface elevations at a site primarily by dewatering granular soil units in the area. Clay units will require more time to dewater, and during this lag time, p-wave velocities in these clay units may still indicate saturated conditions. However, due to the lower permeabilities in the clays, these units may be poor water producers and not pose a significant hindrance to the dewatering operations versus granular soil units.

In application, SRT can be used to delineate phreatic surface elevations prior to dewatering system design and can also be used to indicate locations of relative bedrock highs and lows. Bedrock units often exhibit seismic p-wave velocities well in excess of 6,000 ft/s and, therefore, would appear as high velocity layering beneath a soil unit sequence.

Figure A-12 shows results from an SRT survey conducted along the toe of an embankment dam. The survey results indicate relative highs and lows in the interpreted top of bedrock. The results also indicate possible buried channel features, as shown by relative low velocities in the tomogram. If the site characterization and design did not take these apparent channel features into account, dewatering conditions could be very different than assumed in the design, possibly resulting in inadequate dewatering capacity.

A.1.2.4 Self-Potential

SP surveys characterize subsurface seepage conditions based on the so-called streaming potential that arises in soil and rock materials due to changes in hydrostatic head (Corwin, 2005). Sp surveys are routinely used to assess seepage conditions around earth embankments as a means of characterizing possible internal erosion sites. It is therefore feasible to use the same technology to characterize the flow of subsurface water for dewatering designs. The following discussion is largely based upon material presented in Corwin (2005) and the references listed therein.

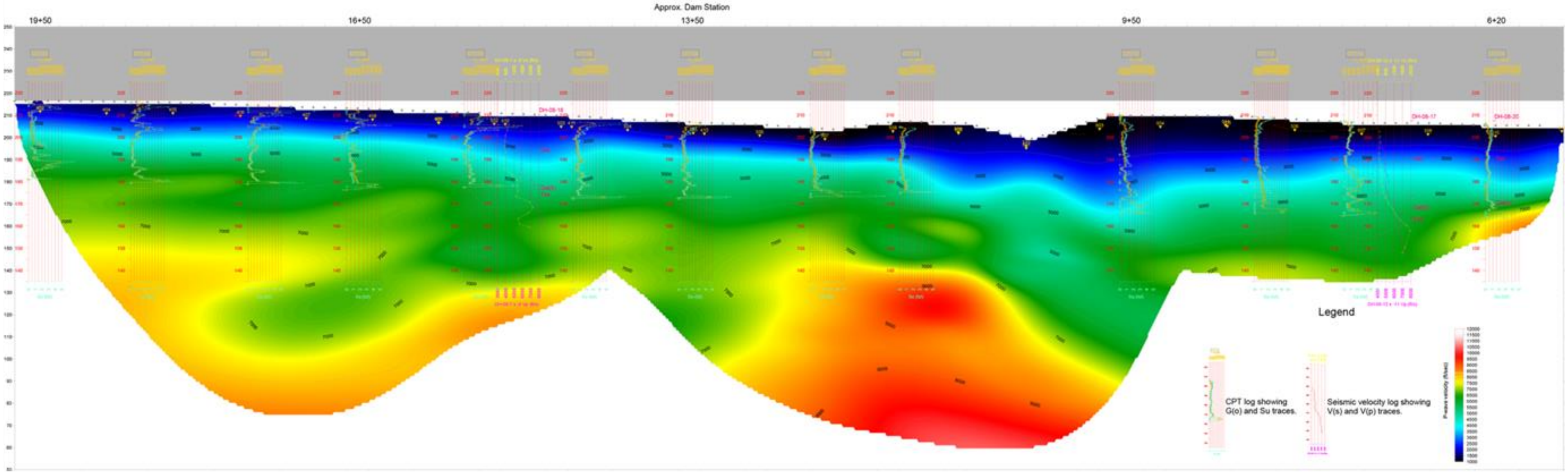
A.1.2.4.1 Streaming Potentials

Soil and rock materials develop an electric double layer when immersed in water. As most mineral grains contain a negative charge on the grain surface, positive charges are attracted from the water to the mineral grain surface. Some of these positive charges are mobile and can be carried along with seepage flow. The result is a net positive around the upstream end of a seepage path and a net negative around the downstream end. The magnitude of the resulting streaming potential voltage is shown in Eq. A-6.

$$\mathrm{V} = \frac{\rho\varepsilon\zeta}{4\pi\eta}\Delta P = C_P \cdot \Delta P \qquad \text{Eq. A-6}$$

where:

V = streaming potential
ρ = pore water ER
ε = pore water dielectric constant
ζ = Zeta potential (a property of the soil mineralogy)
η = water viscosity
ΔP = hydrostatic pressure difference along the seepage path
C_P = streaming potential cross-coupling coefficient



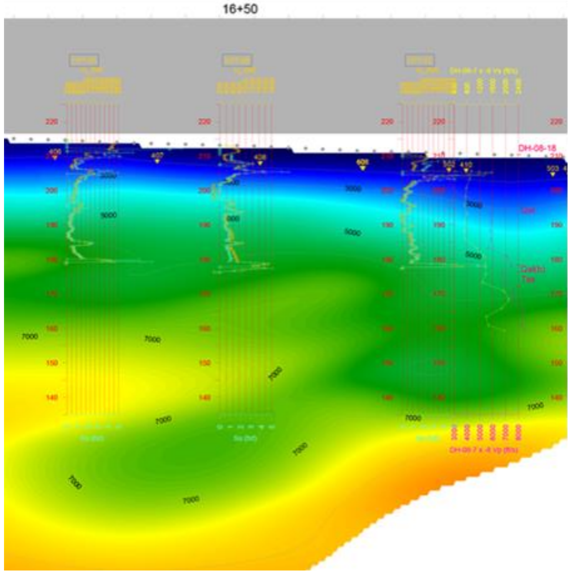


Figure 21.6.7.2-12. (a) Seismic section along the toe of an embankment dam, showing higher velocities (oranges and reds) that indicate bedrock materials. Note the relative highs and lows in the indicated top of bedrock. Also shown are borehole geophysical logs and Cone Penetrometer Test (CPT) log information from the site.

(b) Enlarged portion of the above section, showing lower velocities (greens) adjacent to a)nd beneath higher velocities (yellows), and likely indicating a buried channel feature within the top of bedrock. Note that the CPT and SPT measurements did not extend to the depth of the observed low velocities, as indicated in the accompanying logs. A mischaracterization of the foundation is possible if based upon drilling and CPT alone. (Scoggins Dam, Oregon, Rich Markiewicz, Reclamation)

From Eq. A-6, it is seen that the streaming potential voltage is proportional to the pressure difference and the ER, emphasizing the need to conduct resistivity surveys concurrently with SP surveys. Some flow must occur for the streaming potential to be observed; therefore, subsurface flow conditions are assumed for the foundation being investigated.

A.1.2.4.2 Self-Potential Signatures around Embankment Dams

From the above discussion, SP negative signatures are generally observed at seepage inlets or above areas where seepage is entering the foundation. Likewise, SP positive signatures are generally observed at or above seepage exits. Uniform and nonuniform embankment or foundation seepage each have typical patterns. Nonuniform seepage is of interest, as it may imply preferential seepage flow, which could influence internal erosion and foundation dewatering designs.

Figure A-13 (Bogoslovsky and Ogilvy, 1970) shows a conceptual drawing of SP contours from on and around an embankment having uniform seepage conditions. In portion (a), seepage enters the foundation near the upstream toe, and negative SP values are observed in this area. Seepage exits downstream and is accompanied by positive SP values. Profile data from this same site (portion b) would show more negative values at high pool, as the hydrostatic head difference would be greater.

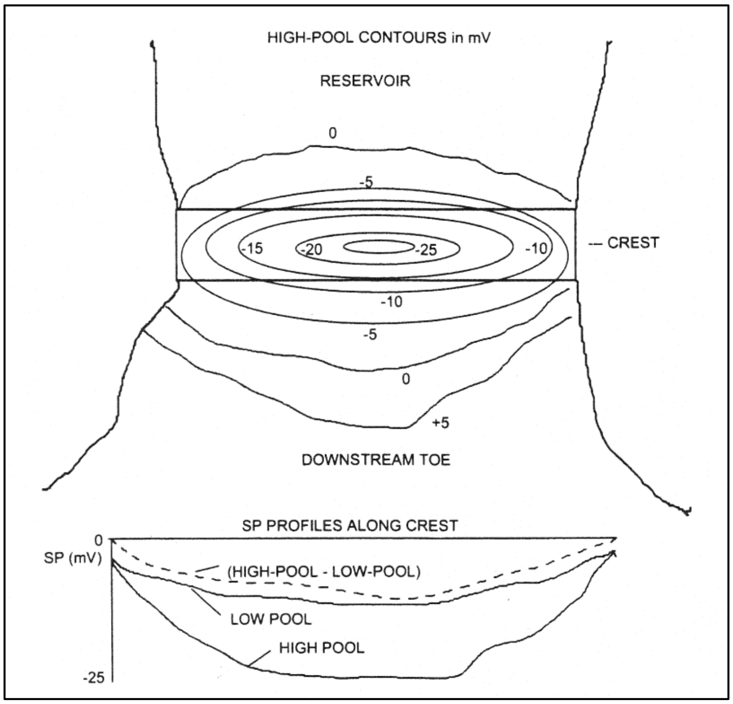


Figure A-13. SP values from uniform seepage on and around an embankment dam: (a) plan view, (b) section view.

Nonuniform seepage (figure A-14; Bogoslovsky and Ogilvy, 1970) is expected to yield SP contours with much more irregular shapes, (b)-(c), as the seepage path's geometry and flow rates will vary both horizontally and vertically. In dam foundation soils, soil gradation changes can also contribute to changes in the observed SP, as soil changes may be accompanied by changes in the coupling coefficient or the permeability and, hence, hydrostatic head gradient.

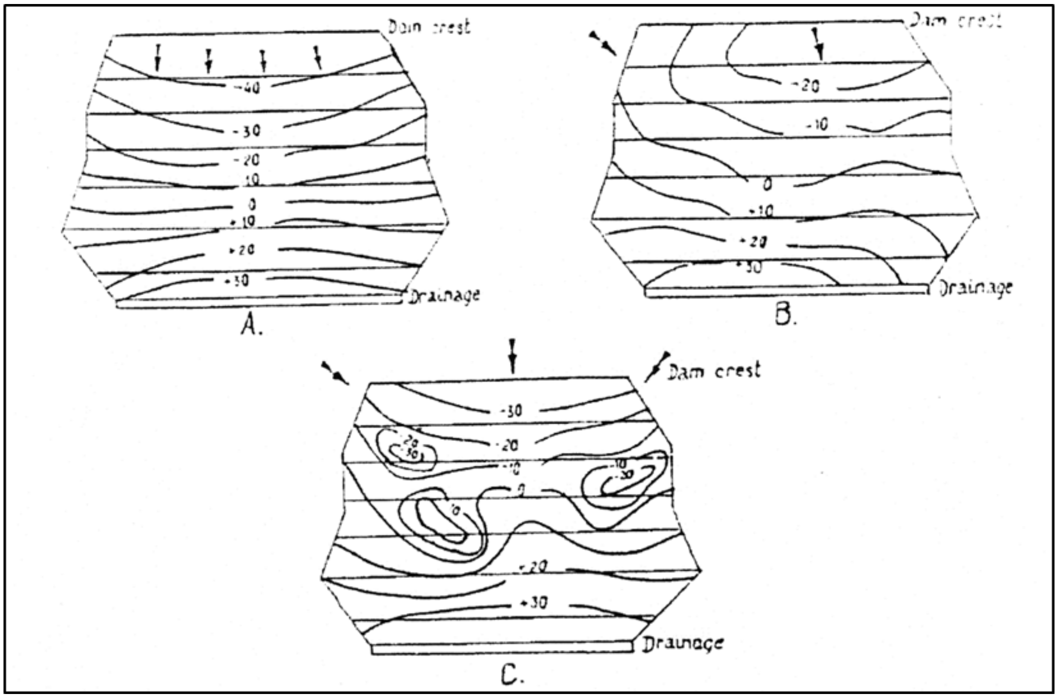


Figure A-14. SP values from uniform and nonuniform seepage on and around an embankment dam: (a) uniform seepage, (b) seepage entering from abutments, (c) nonuniform seepage with soil type changes.

Figure A-15 shows results from an SP survey conducted along an embankment crest. Several areas of possible seepage were observed in this survey. When applied to dewatering design programs, SP and resistivity surveys conducted together can indicate areas of likely seepage paths in embankment and foundation materials.

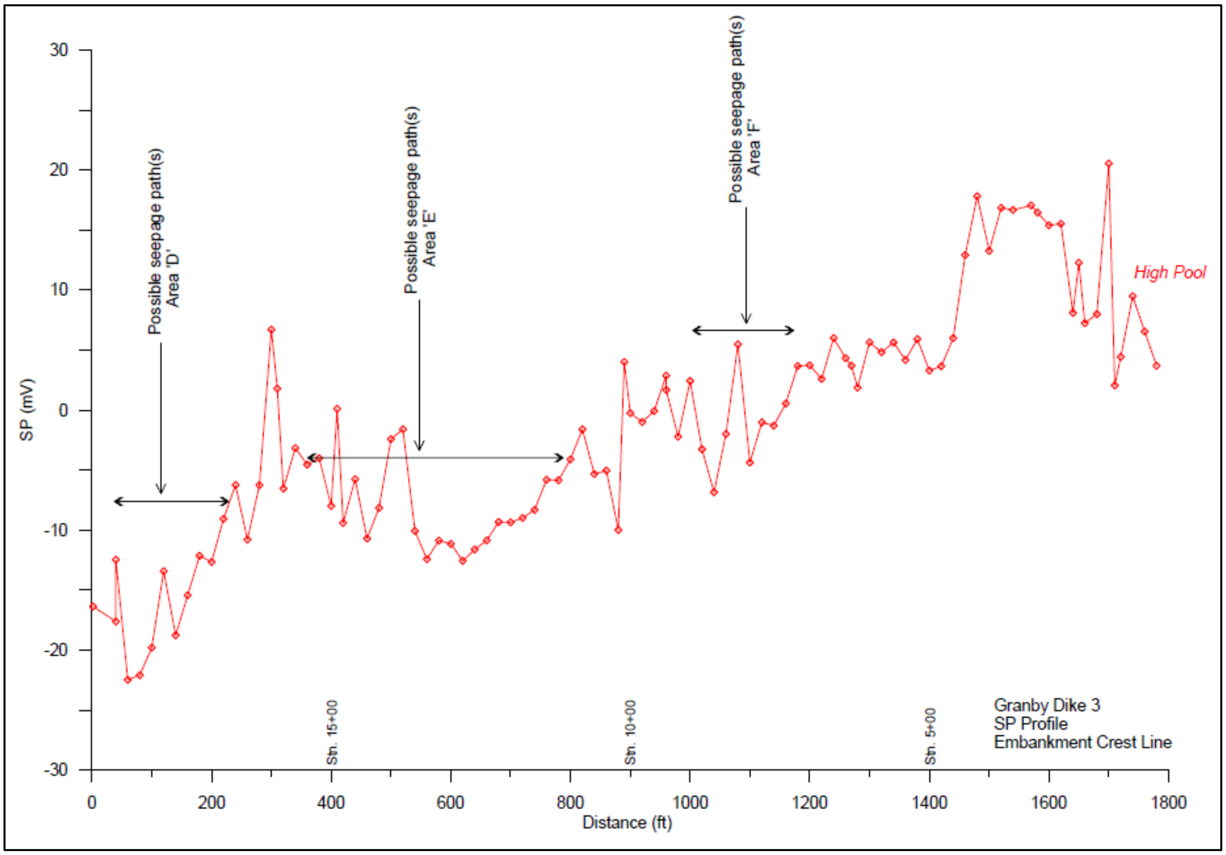


Figure A-15. SP survey on an embankment crest showing possible nonuniform seepage through or beneath the embankment.

A.1.3 Borehole Geophysical Methods

Numerous types of borehole geophysical methods exist. However, most borehole methods used for groundwater applications are logging methods. Geophysical borehole logging consists of measuring various physical properties of geologic materials surrounding a borehole. A geophysical log is obtained by making measurements with an instrument lowered into a borehole and recording the data with a device located on the ground surface. Interpretation of geophysical logs may furnish qualitative information, and sometimes quantitative information, about the characteristics of subsurface materials.

The three most relevant borehole geophysical testing methods (based upon common usage and their ability to identify aquifer parameters) are discussed below.

A.1.3.1 Resistivity

The ER log is widely used to correlate formations in the oil and gas industry and to obtain some estimation of reservoir content. ER in the water industry is hampered by a number of factors that limit its application and tend to obscure the usefulness of readings. Such factors include:

- The borehole size
- The casing size and material (especially steel casing) if present
- The resistivity of any drilling mud used or remaining in the borehole
- The potential infiltration of drilling mud into the water-bearing formation
- The presence of, and conductivity of, connate water and/or post-depositional recharge/replacement water
- The relative thickness of the strata to the logging tool electrode spacing
- The degree of homogeneity or heterogeneity of the formation(s)

All of these physical limitations compound the inherent uncertainty of the significance of the ER readings, due to simply not knowing the relationship between ER and in situ hydraulic conductivity (***K***).

Advances in drilling technologies have minimized or mitigated the influences of most of the factors mentioned above. As more correlations between in situ testing and ER logs are determined, and more lab results of core samples and water samples are obtained and correlated with the ER logs, a data base of empirical relationships can be built up so that for that particular area, ER logs can become very reliable in estimating ***K*** values (Archie, 1942).

However, even up to 2011, the relationship between ER and ***K*** remained one of the least understood relationships in hydrogeophysics. As stated by Ahmed et al. (1988):

> *"The relationship between hydraulic conductivity and electric resistivity is one of the most difficult and challenging approaches in the field of hydrogeophysics. The promising side of this relation is the analogy between electric current flow and water flow, whereas the grand ambiguity is the non-dimensionality between both two quantities. Relationship between hydraulic conductivity and electric resistivity either measured on the ground surface or from resistivity logs, or measured in core samples has been published for different types of aquifers in different locations. Generally, these relationships are empirical and semiempirical, and confined in few locations.*

> *This relation has a positive correlation in some studies and a negative in others. So far, there is no potentially physical law controlling this relation, which is not completely understood."*

Acoustic (and seismic) methods, while not capable of determining hydraulic properties of water-bearing strata, are very useful in establishing bedrock contours, water table contours, lithologic changes in the strata, and other controls on the vertical and lateral extent of aquifer materials or strata.

A special type of seismic study, cross-hole seismic tomography, can be used to image specific structures within a zone between boreholes. Properties that can be estimated are: material type, degree of compaction or cementation, porosity, saturation, and fracturing. All of these properties can influence ***K***. Typical borehole spacing is 50 feet or less, so a potentially large number of cross-hole pairs would be needed to image a large project area.

A.1.3.2 Flowmeter Logging

While it is not a direct measurement of aquifer properties, vertical flowmeter logging is a useful tool when used in conjunction with other downhole geophysical logging methods. Flowmeter data can be used in the design and interpretation of in situ hydraulic testing, identifying zones or layers for chemical water sampling, identifying target zones to screen and/or zones to seal off, and in refining a conceptual model of a project site.

Single-hole vertical flowmeter logging can be used to directly measure the rate of vertical flow and the direction of vertical flow within discrete zones of the borehole. Additionally, the vertical flowmeter log can be used to establish relative hydraulic gradients and to identify transmissive zones, layers, or fractures within the borehole profile.

Cross-hole flowmeter logging utilizes two closely spaced wells, in which one well is pumped at a constant rate (or water is injected at a constant rate) and a flowmeter survey is conducted in the adjacent hole. The holes must be close enough together so that pumping in one well causes effects in the second well. Cross-hole flowmeter data can identify cross-hole connections and provide data that can be used to estimate transmissivity, head, and/or storage coefficients when used in conjunction with other bore-hole testing.

Flowmeters are generally either heat-pulse flowmeters (HPFM), electromagnetic flowmeters (EMFM), or spinner flowmeters (figure A-16). The characteristics and uses of each type of flowmeter are discussed in *Vertical Flowmeter Logging* (U.S. Geological Survey, 2011).

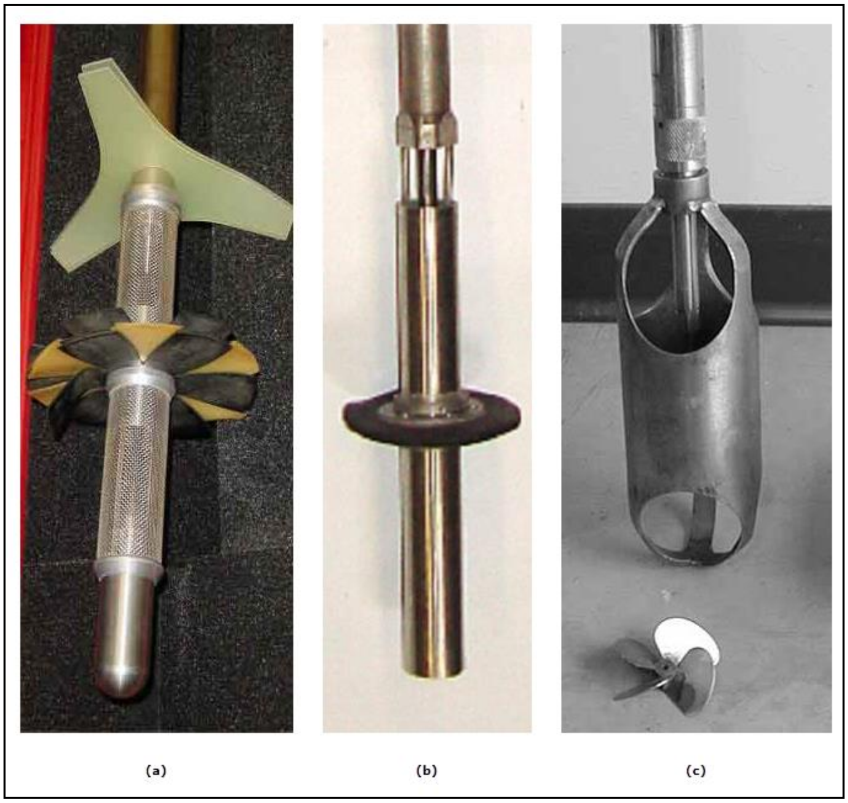


Figure A-16. Photos of three main types of flowmeters: (a) HPFM tool heat grid and sensor area fitted with diverter, (b) EMFM tool sensor area, and (c) spinner flowmeter cage and sensor area, with impeller blades displayed next to tool (modified from U.S. Geological Survey, 2011).

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