

GROUNDWATER AND WELLS



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Workshop Outline



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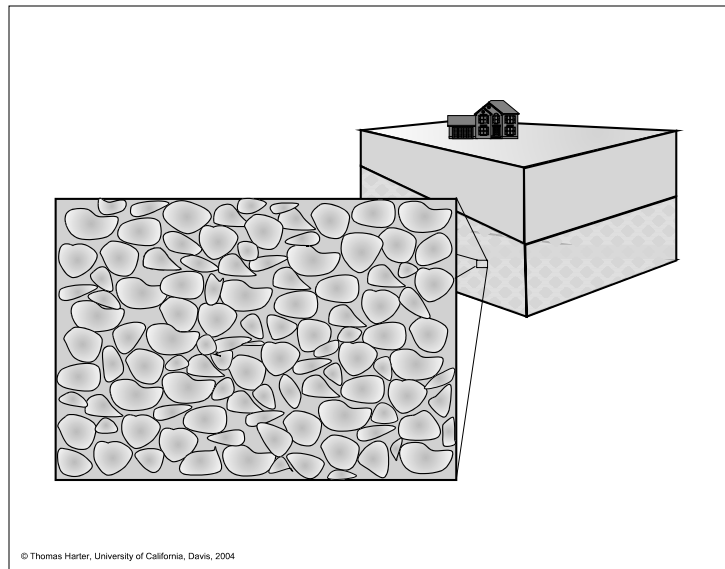
2

What is Groundwater?

- An underground lake?
- A network of underground rivers?
- A rectangular network of pipelike water arteries?
- A giant sponge?

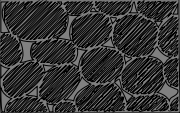
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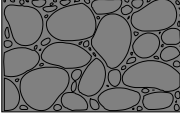


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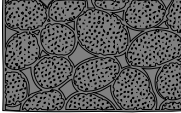
Groundwater in Different Sediments and Rocks



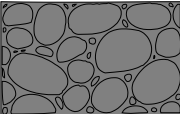
well-sorted sediment



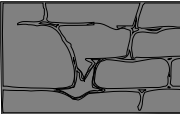
poorly sorted sediment



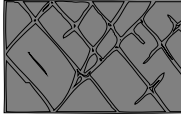
porous sediment



consolidated sediment



dissolution of rock



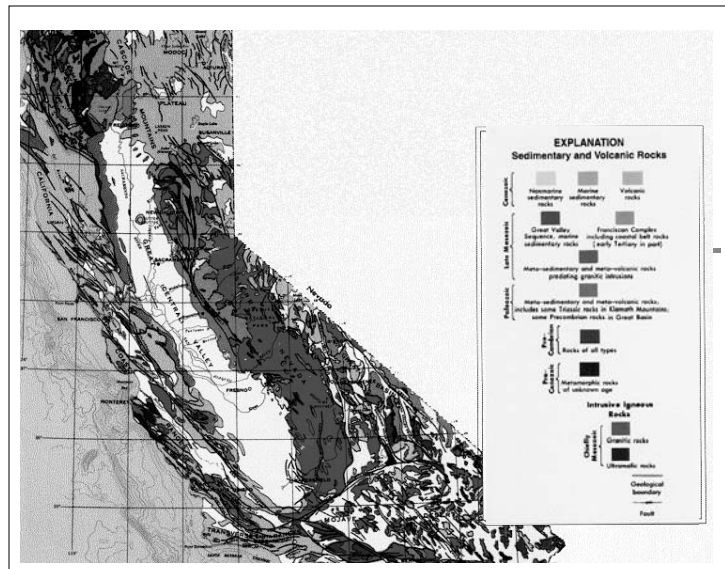
rock fractures

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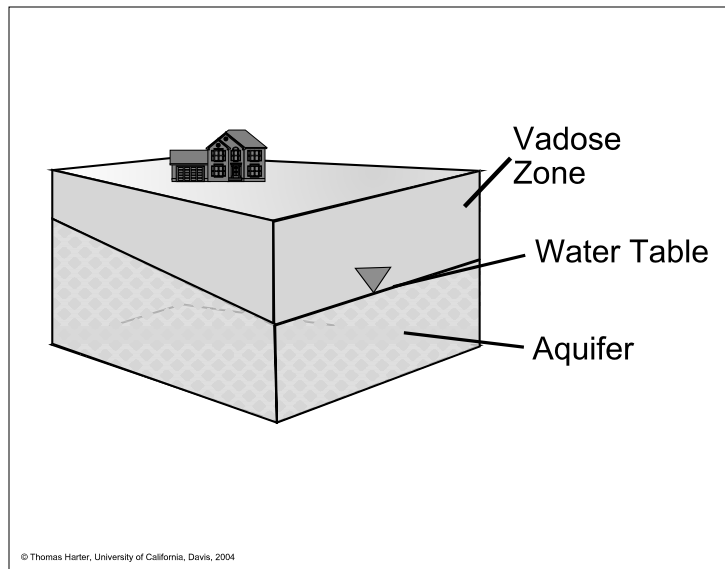
5

general type	origin	material	name
unconsolidated	glaciers	sand, silt, clay	till, outwash
	water: rivers, lakes, ocean deposits	gravel, sand, silt, clay, organic matter	alluvial sediments, fluvial sediments, marine sediments
	wind	silt, sand	loess, sand dunes
consolidated	lithified sediments	sand silt clay	sandstone, siltstone, shale, conglomerate,
	chemical sediments	gravel, sand, silt calcium carbonate calcium sulfate	limestone, dolomite gypsum
	igneous rocks		granite basalt
	metamorphic rocks	sandstone shale limestone granite	quartzite slate marble gneiss

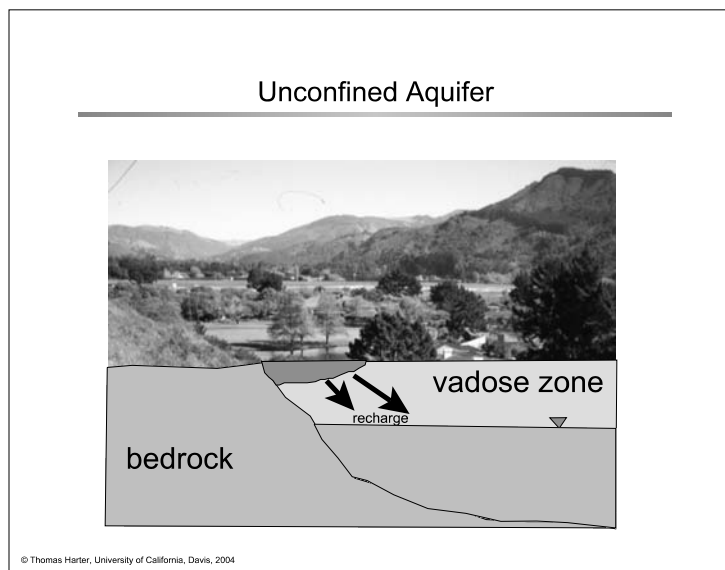
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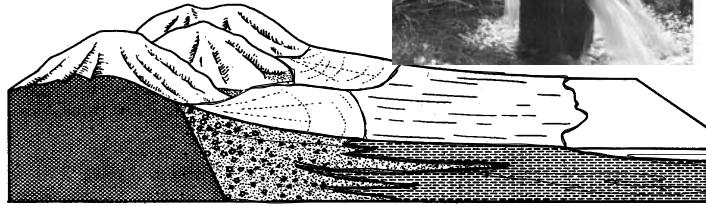


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Confined (or: Artesian) Aquifer

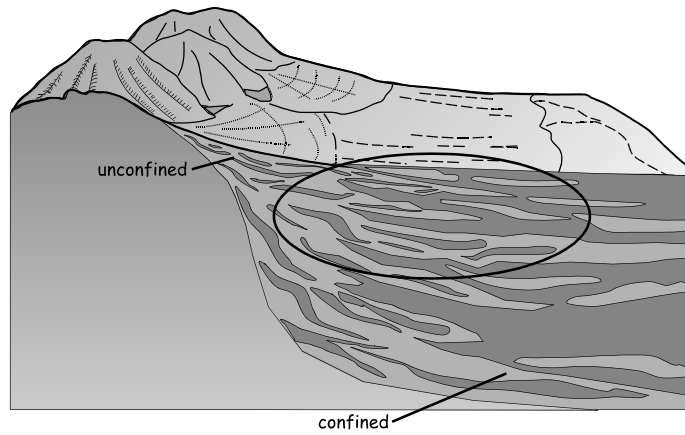


Confined aquifers created by deposition of alternating layers of permeable sand and gravel and impermeable silts and clays deposited in intermontane basins.

adopted from: Fetter, 1988

10

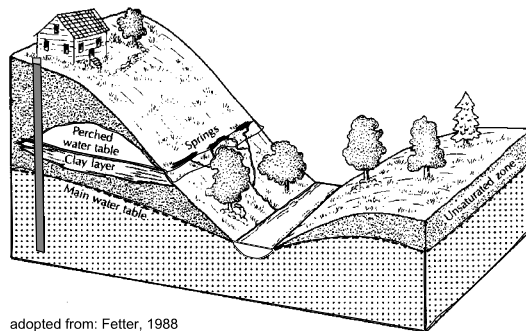
Semi-Confined Aquifer



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Perched Water Table



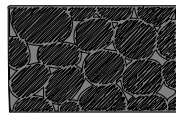
adopted from: Fetter, 1988

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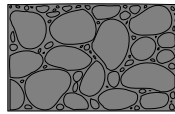
12

How much groundwater is in an aquifer?

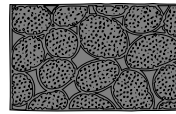
As much as there is pore space?



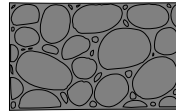
well-sorted sediment



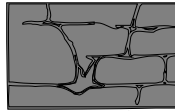
poorly sorted sediment



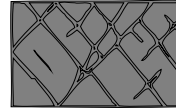
porous sediment



consolidated sediment



dissolution of rock

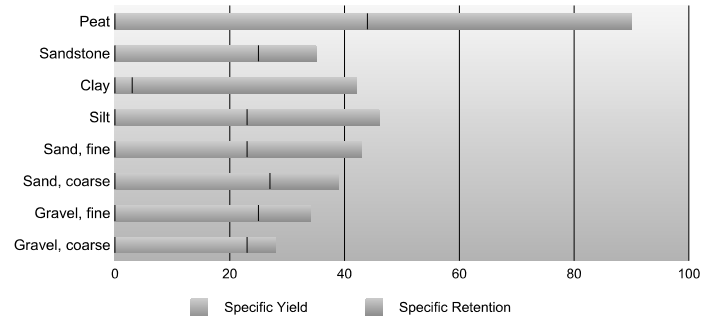


rock fractures

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Porosity and Specific Yield of Selected Materials in %

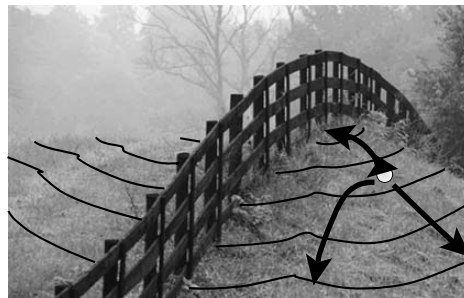


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In which direction and how fast does groundwater flow?

Same principle as a ball on a hill ...



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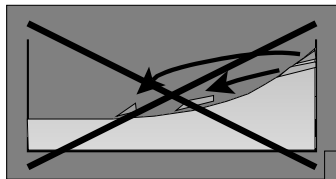
Downslope across the contours!



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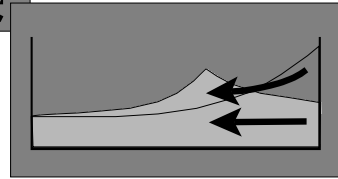
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Beware: not quite like a ball -



more like water in a tub

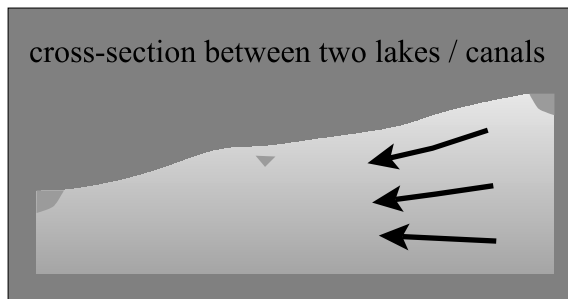
cross-section of a tub



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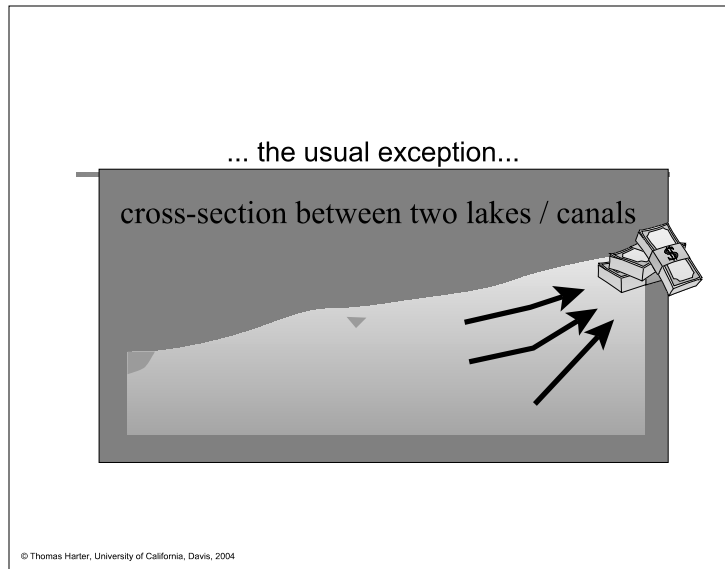
17

cross-section between two lakes / canals

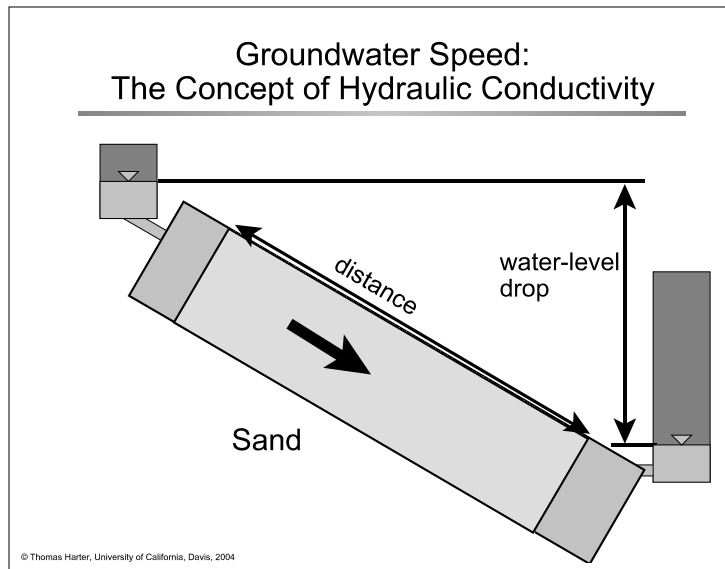


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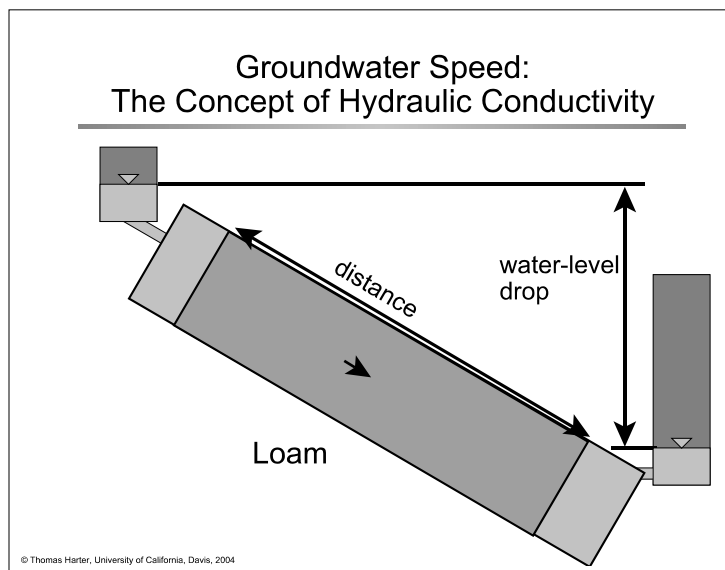
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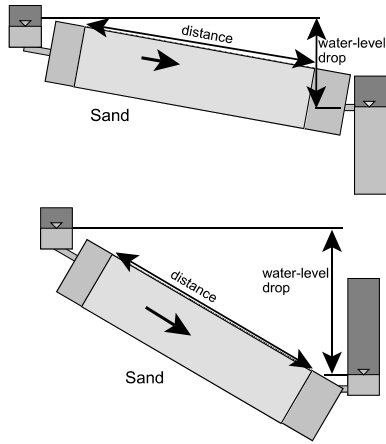


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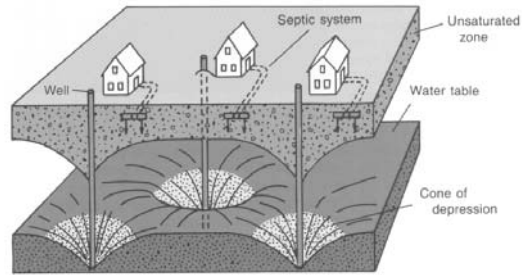
Groundwater Speed: The Concept of Hydraulic Gradient



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Cone of Depression



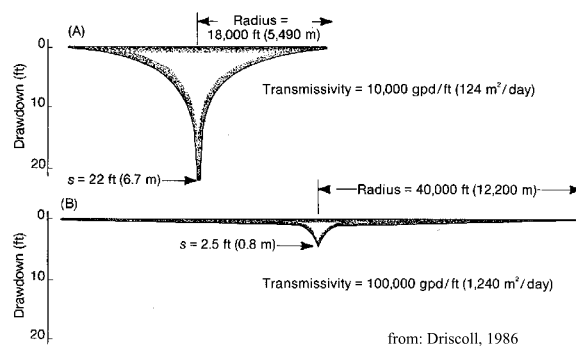
Effect of concentrated housing on ground-water level.

from: U.S. Geological Survey, 'Ground Water and the Rural Homeowner'

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Influence of Transmissivity on Cone of Depression



from: Driscoll, 1986

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Specific Capacity of a Well

Specific capacity of a well =
amount of pumpage per foot of drawdown.
(measured as gpm/ft)

- ▶ very low: 1 gpm/ft; very high: 100 gpm/ft
- ▶ approximately proportional to hydraulic conductivity
- ▶ decreases with time during pumping test
- ▶ decreases with increased pumping rate
- ▶ decreases with lower water level in a well
- ▶ larger in a properly designed and developed well
- ▶ affected by land subsidence

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What is the practical meaning of hydraulic conductivity and transmissivity?

- ▶ An aquifer with double the conductivity will yield double as much water at the well.
- ▶ A confined aquifer with double the thickness will yield double as much water at the well.
- ▶ At the same pumping rate, well drawdown in a confined aquifer will be half as much at double the hydraulic conductivity (**specific capacity of well is doubled**).
- ▶ Water will flow double as fast from a leaking river or canal, if the hydraulic conductivity below the river / canal and in the aquifer is double as large.

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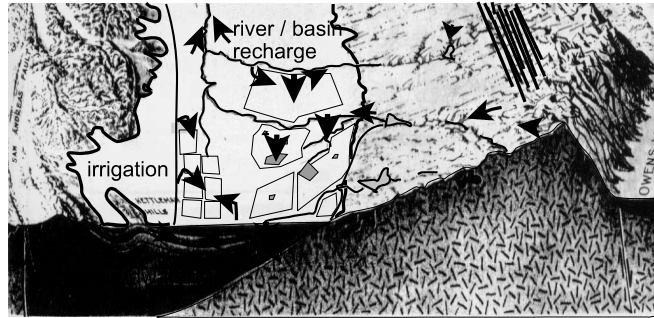
Where does groundwater come from and where does it eventually go?

- The Hydrologic Cycle -

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Groundwater in California's Valleys



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Water Well Construction

The major steps in installing a good well

- ▶ Well Location and Design
- ▶ Well Drilling
- ▶ Well Installation
- ▶ Well Development
- ▶ Pump Installation
- ▶ Well Water Quality Protection
- ▶ Collection and Analysis of Pumping Test Data

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How do we find out where to drill a well?

Groundwater Exploration Techniques

- ▶ Well driller's experience

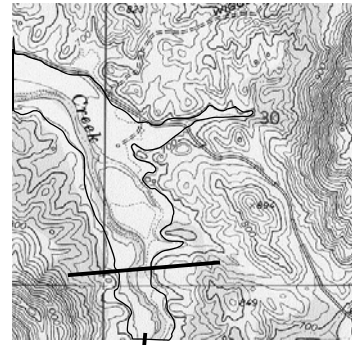
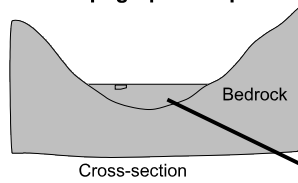
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How do we find out where to drill a well?

Groundwater Exploration Techniques

- ▶ Well driller's experience
- ▶ **Topographic maps**



Valley floor (=> the "bathtub")

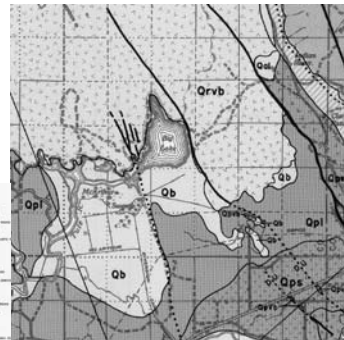
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How do we find out where to drill a well?

Groundwater Exploration Techniques

- ▶ Well driller's experience
- ▶ Topographic maps
- ▶ **Geologic, hydrogeologic, hydrogeochemical maps**



from: CaDWR Bulletin 98

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How do we find out where to drill a well?

Groundwater Exploration Techniques

- ▶ Well driller's experience
- ▶ Topographic maps
- ▶ **Depth to groundwater**

<10'
50'
>100'
>200'
>400'



from: CaDWR, 1992

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How do we find out where to drill a well?

Groundwater Exploration Techniques

- ▶ Well driller's experience
- ▶ Topographic maps
- ▶ Geologic, hydrogeologic, hydrogeochemical maps
- ▶ **Aerial photographs, satellite images**
 - Vegetation types



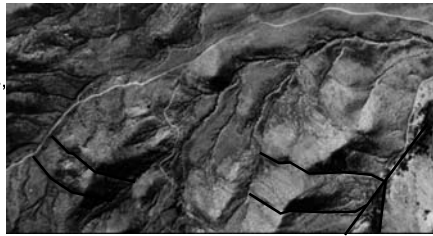
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How do we find out where to drill a well?

Groundwater Exploration Techniques

- ▶ Well driller's experience
- ▶ Topographic maps
- ▶ Geologic, hydrogeologic, hydrogeochemical maps
- ▶ Aerial photographs, satellite images
 - Vegetation types
 - Landforms
 - Drainage patterns
 - Fracture traces and lineaments**



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Other Well Location Criteria

- ▶ Accessibility for drilling and service equipment
- ▶ Distance / elevation gain to end use
- ▶ Existing groundwater contamination

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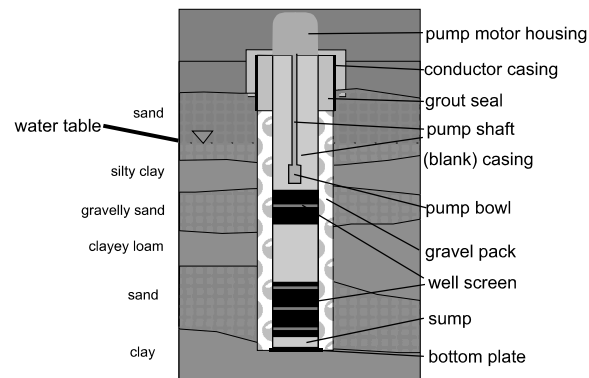
Other Well Location Criteria

- Potential groundwater contamination
 - Unfavorable topography, e.g. low spot
 - Storage areas of chemicals
 - Gasoline and other underground storage tanks
 - Nearby streams
 - Septic tanks (not an issue for irrigation wells)
- ===> well should be sufficiently upgradient ("uphill") from potential sources
- Location of nearby wells
- Local ordinances and state regulations

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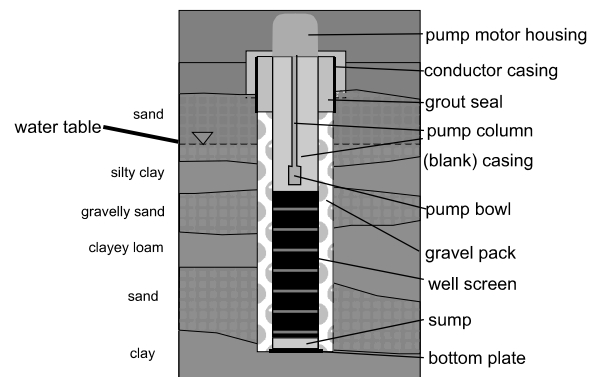
Water Well: Principal Components



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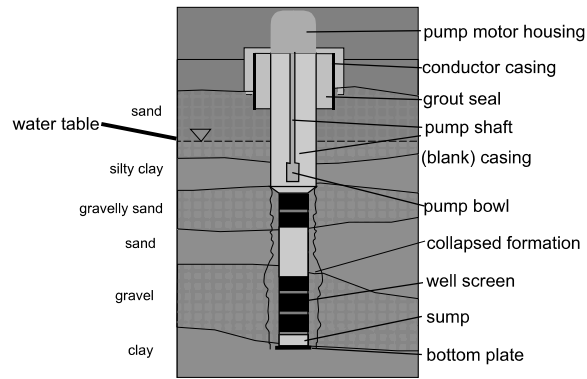
Water Well with Continuous Screen



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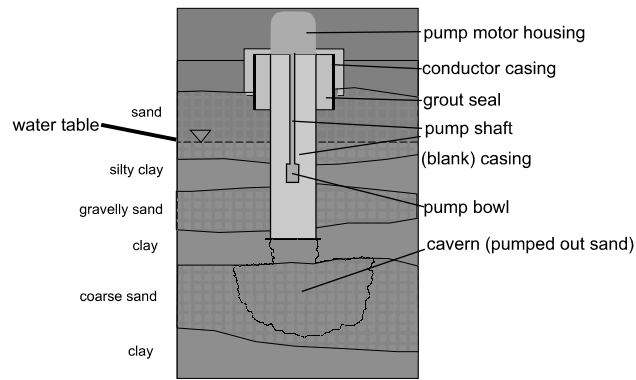
Water Well with Natural Pack



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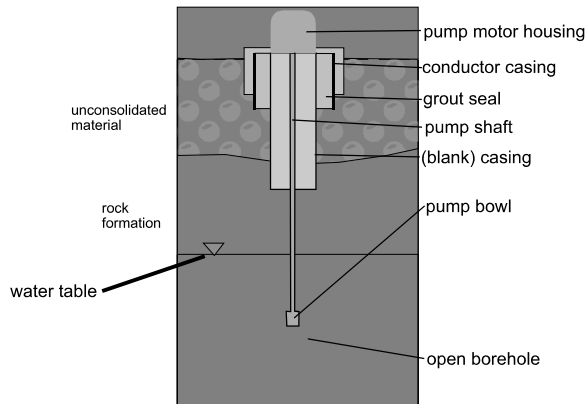
Open Bottom Well in Unconsolidated Material



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Water Well in Hard Rock

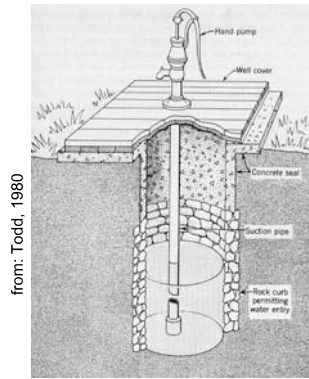


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Well Drilling Techniques

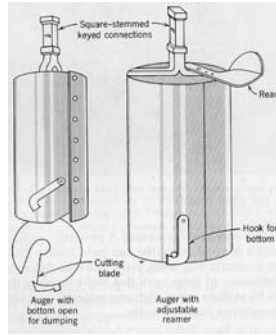
- Hand-dug wells
- Auger drilling
- Cable tool drilling
- Rotary drilling
- Reverse rotary drilling
- Air drilling
- Driven wells



from: Todd, 1980

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Well Drilling Techniques



Bucket auger
(from: Todd, 1980)

Solid stem auger
(from: Driscoll, 1986)



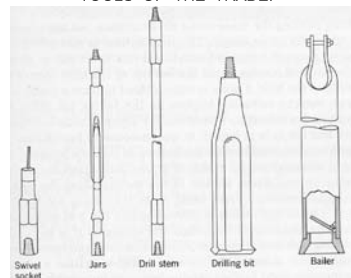
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Well Drilling Techniques

- Hand-dug wells
- Auger drilling
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- Driven wells

TOOLS OF THE TRADE:



from: Todd, 1980

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Cable-Tool Rig

► Advantages:

- Useable in almost all types of formation
- Very practical in unconsolidated material with rocks and boulders
- Inexpensive drilling rig, small crew (1-2)
- Low equipment maintenance
- Stabilized borehole during drilling
- Reliable formation and water samples can be collected from any depth
- Rigs can go into rugged terrain
- Little make-up water required
- No additives required
- No lost circulation
- Estimates of yield at any depth from bailing

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Cable-Tool Rig

► Disadvantages

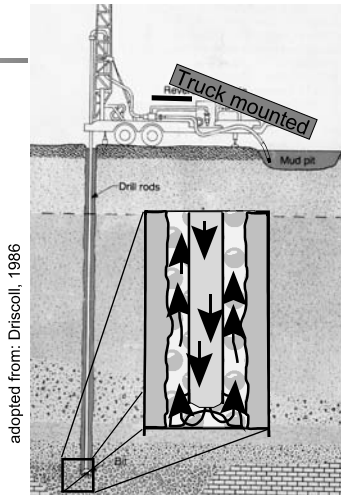
- Slow penetration rate
- Penetration rate depends on borehole diameter
- Higher casing cost (heavier wall)
- Difficulties with pulling back (to expose screen) in some formations
- (Need for telescoping well for depths beyond 700 ft)

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Well Drilling Techniques

- Hand-dug wells
- Auger drilling
- Cable tool drilling
- Rotary drilling
- Reverse rotary drilling
- Air drilling
- Driven wells



adopted from: Driscoll, 1986

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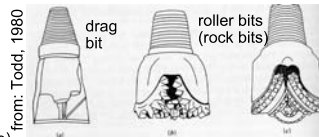


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Operation of a Rotary Drilling Rig

- Drill string assembly:
 - Drill bit (drag or cone)
 - Drill collar(s) or stabilizers
 - Drill pipe
 - Kelly (square, hexagonal, or fluted pipe)
 - Rotating motion: drive shaft => rotary table => kelly
 - Alternative: top-head drive
- Water circulation:
 - Pit
 - Mudpump
 - Hose
 - Water swivel
 - Drill pipe
 - Nozzles in drill bit



from: Todd, 1980



from: Driscoll, 1986

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Rotary Drilling Fluids

Purpose

- Lift cuttings from bottom of borehole to surface
- Support and stabilize borehole wall
- Seal borehole to prevent fluid loss
- Suspend cuttings when circulation is stopped
- Cool and clean the drill bit
- Lubricate bit, bearings, mud pump, and drill pipe

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Rotary Drilling Fluids

Additives

- Clay from native formations: muddy water
- Water with clay (bentonite) additives
- Water with polymer additives

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Rotary Drilling: Advantages

- High penetration rates
- Minimal casing required during drilling
- Rapid rig mobilization and demobilization
- Ease of setting well screens as part of setting casing
- Very effective for small diameter domestic and shallow wells

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Rotary Drilling: Disadvantages

- ▶ Larger crew than cable tool for greater depth (at least 2-3)
- ▶ Collection of accurate sample requires separate split spoon sampling / coring
- ▶ Use of drilling fluid may plug formations
- ▶ Additional knowledge and management for handling drilling fluids necessary
- ▶ Theoretical limitation: large diameter hole (>22 inches) => upward flow velocity in annulus too small (in practice, even larger diameter holes are drilled w/ rotary)
- ▶ Desanders and shale shakers required to preclude recirculation of drill cuttings, collect formation samples, and prevent plugging of sand formations w/ clay

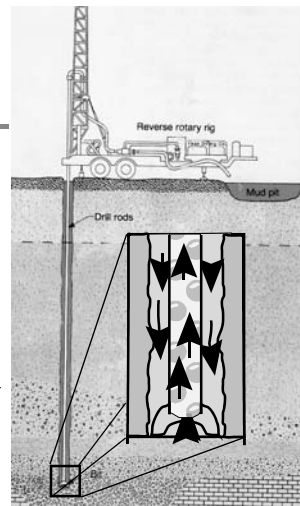
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Well Drilling Techniques

- ▶ Hand-dug wells
- ▶ Auger drilling
- ▶ Cable tool drilling
- ▶ Rotary drilling
- ▶ Reverse rotary drilling
- ▶ Air drilling
- ▶ Driven wells

adopted from: Driscoll, 1986



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Photo: Courtesy of Allan Fulton

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Reverse Rotary Drilling

Difference to Rotary Rigs

- ▶ Most efficient for large diameter wells in unconsolidated formation
- ▶ Also used in soft consolidated rocks (e.g., sandstone); hardrock (in conjunction with air rotary drilling)
- ▶ Similar in function to rotary, typically mounted on long-bed trailer
- ▶ Typically uses airlifting to pump drilling fluid (use of air compressor)
- ▶ In theory, native (muddy) water used as drilling fluid; in practice, organic polymers and bentonite commonly used as additives (particularly in deep wells)

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Reverse Rotary Drilling

Advantages

- ▶ Most advantages method for large capacity wells in unconsolidated deposits
- ▶ Porosity and permeability of formation near borehole relatively undisturbed
- ▶ Large diameter holes can be drilled quickly and economically
- ▶ Little chance for washout in borehole (low fluid velocity)
- ▶ Can minimize or eliminate addition of mud
- ▶ *see rotary drilling*

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Reverse Rotary Drilling

Disadvantages

- ▶ Large water supply usually needed
- ▶ Large mud pits required (3 x borehole volume)
- ▶ Some sites inaccessible due to rig size (alternative: cable-tool)
- ▶ Larger crew than for cable tool (2-4)

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Well Drilling Techniques

Most common method in most California hardrock areas (Sierra, Coast Range, Northeastern CA)

- Hand-dug wells
- Auger drilling
- Cable tool drilling
- Rotary drilling
- Reverse rotary drilling
- Air drilling
- Driven wells



from: Driscoll, 1986

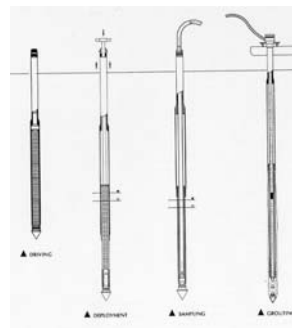
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from: Geoprobe Systems Inc., 1996

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Well Logging



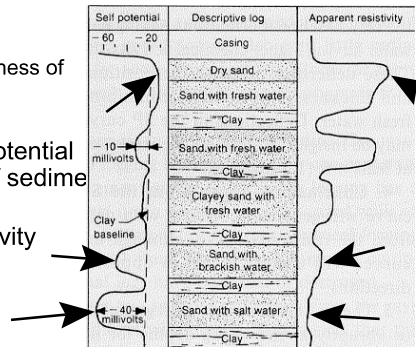
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The Electric Log or E-log

Purpose:
determine depth and thickness of permeable zones

- Spontaneous potential (Self-potential of sediments)
- + Apparent resistivity



from: Driscoll, 1986

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Well Screen Design

► Functions:

- Access for sufficient well development
- Minimal incrusting tendency
- Low head loss
- Control sand pumping
- Optimum specific capacity

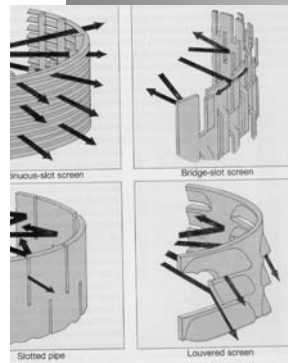
► Criteria:

- Large / sufficient percentage of open area
- Nonclogging slots
- Resistant to corrosion
- Sufficient column, tensile, and collapse strength
- Location within aquifer

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Screen Types

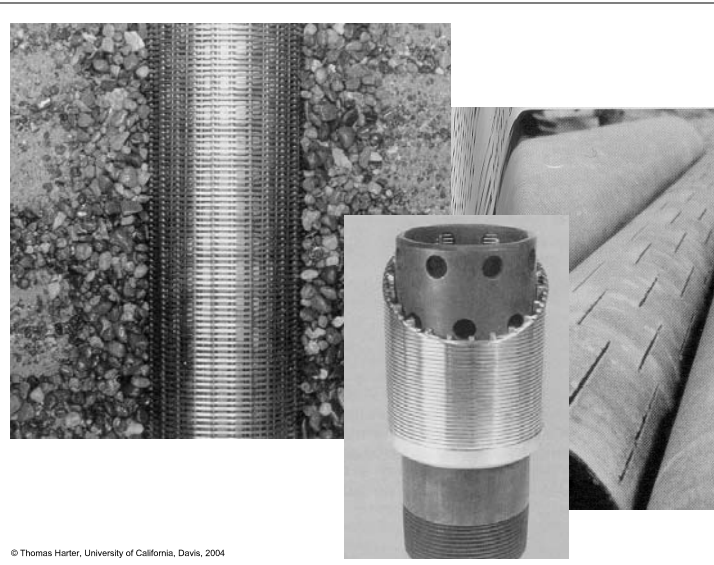


From: Roscoe Moss, 1990

- ▶ Continuous slot wire-wound screen
 - Large open area
 - Triangular shape of wire prevents sand clogging
 - High hydraulic efficiency (one condition of good spec. capacity)
- ▶ Wire-wound perforated pipe
 - High strength
 - Most expensive
- ▶ Louvred or bridge-slot
 - Limited percent open area
 - Sand clogs opening
- ▶ Slotted pipe (horizontal or vertical)
 - Several cutting methods: mill sawed (most accurate), cutting torch, casing perforator, in-place punching (least accurate)
 - Small percent open area (3% - 10%)
 - Very low hydraulic efficiency
 - Well development limited and inefficient
 - Least expensive

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Screen and Casing Materials

- ▶ Materials:
 - Metals and metal alloys; most common: steel
 - Plastics
 - Concrete
 - Others
- ▶ Available slot size: from 0.010 inch to 0.150 inch
- ▶ Use of multiple metals may lead to galvanic corrosion

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Criteria to Determine Slot Size and Screen Length

- % open area \approx % porosity in aquifer formation (10% - 30%)
- Maximum entry velocity < 6 ft / min.
- Slot size small enough to permit only 10% smallest particles in gravel pack (50% of aquifer formation if naturally packed)
- Screen bottom 70% - 80% of confined aquifer / if heterogeneous: permeable strata only
- Screen bottom 1/3 - 1/2 of unconfined aquifer
- Top of screen lower than anticipated drawdown

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Gravel Pack or Natural Pack?

- Filter packing increases effective radius of the well (higher yield, higher spec. capacity)
- In San Joaquin Valley, Salinas Valley, Southeast Desert Basins: always gravel packed
- In hardrock wells: casing landed at top of bedrock, no filter pack
- Natural pack only, where screen is set in medium to coarse sand and gravels

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Gravel Pack Design

- Gravel should be uniform (Uniformity coefficient = $\text{diam}_{.40\% \text{ retained}} / \text{diam}_{.90\% \text{ retained}}$ should be 2.5)
-> less separation during installation, lower head loss, improved specific capacity
- Gravel should be clean and well rounded
-> less development time, less head loss, higher yield, more effective development
- Gravel should contain more than 90% silica
-> no loss of gravel pack volume due to dissolution
- Practical thickness: 3 inches - 8 inches

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Well Casing

► Well Casing:

- W/ cable tool: driven; w/ rotary: lowered into larger hole
- Maintains open hole from ground surface to aquifer
- Structural support
- Isolates contaminated aquifers/aquitards from well
- Material:
 - Production well: wrought iron, alloyed and unalloyed steel
 - Monitoring well: PVC, stainless steel

► Conductor (Surface) Casing:

- Installed through upper strata only
- Support unstable material during drilling
- Reduce loss of drilling fluid
- Facilitate installation and removal of well casing
- Aid in placing sanitary seal
- Reservoir for gravel pack

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Well Casing Diameter

Well Yield (gpm)	Size of Pump Bowl (in.)	Optimum Size of Well Casing (in.)
< 100	4	6
75-175	5	8
150-350	6	10
300-700	8	12
500-1,000	10	14
800-1,800	12	16
1,200-3,000	14	20 *
2,000-3,800	16	24 *
3,000-6,000	20	30 *

From Driscoll, 1986

*In practice, large capacity wells are often designed w/ casing diameter = bowl size + 2"

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Water Well Development

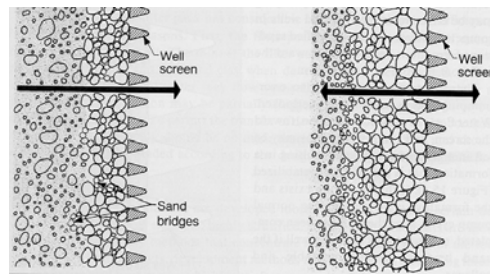
Purpose

- Repair damage to formation around borehole (increase porosity and permeability reduced by shearing, clay / mud cake)
- Remove fines from gravel pack and nearby aquifer formation
- Avoid cementation/incrustation caused by abnormally high flow in limited areas around screen
- Increase specific capacity / efficiency of well
- Prevent sanding
- Obtain maximum well life

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Importance of Development



from: Driscoll, 1986

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Water Well Development

Implementation

- (Test) Pumping: Overpump
 - Will affect only area near top of screen
 - Causes bridging / instable gravel pack
 - Very inefficient for well development
 - Specific capacity only $\frac{1}{4}$ - $\frac{1}{2}$ of optimally developed well
 - Do not use permanent pump for development (excessive wear due to sanding)

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Water Well Development

Implementation

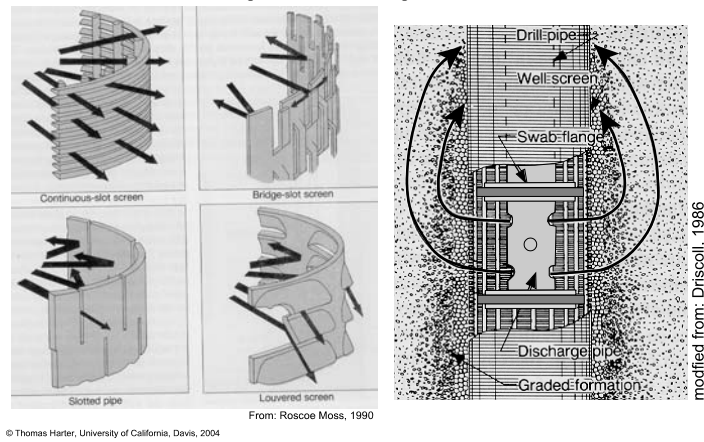
- Surging
 - Backwashing (rawhiding) with test pump
 - Mechanical surging:
 - Surge block, surge plunger, swab
 - Most common locally: double-flanged swab
 - Mechanical surging with double-flanged swab very effective
 - Short-term cost increase: \$20 - \$30 / ft. in drilling cost
 - Long-term cost savings:
 - 50% - 200% higher specific capacity => less pumping cost
 - Sand-free pumping => less maintenance, longer lifetime of well

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Surge & Airlifting

e.g., double-flanged swab

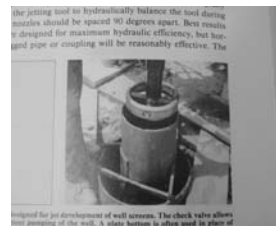


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Water Well Development

Further Development Techniques

- Air surging
- Backwashing with air
- Hydraulic jetting (hardrock aquifers, sand and gravel aquifers)
- Hydraulic fracturing (hardrock aquifers)



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Purpose of the Pumping Test

- Determine properties of the pumping well:
 - Specific capacity of the well
- Determine aquifer properties:
 - Transmissivity T
 - Storage coefficient S (confined conditions)
 - Specific yield (unconfined conditions)
 - (Aquifer boundaries and their effects)
 - (Leakage through aquitards)
 - (Aquitard storage)

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Water Well Design Objectives

- Highest yield with minimum drawdown = *High Well Efficiency (> 80%)*

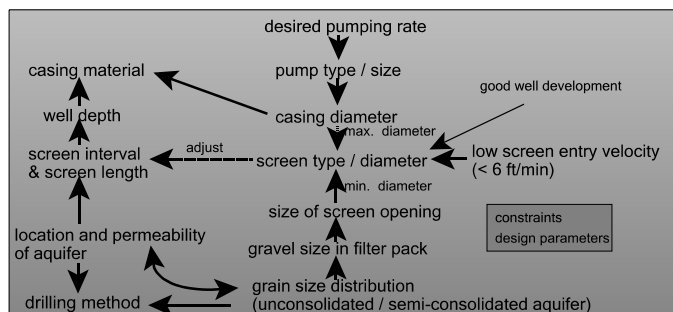
Well Efficiency = ratio of actual specific capacity to optimal specific capacity

- Good quality water with proper protection from contamination
- Sand free water
- Long lifetime (> 25 years)
- Reasonable short-term and long-term costs

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Water Well Design Criteria

Basic Decision Tree



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Cost of Poor Well Design

- If the extra lift due to well losses (well inefficiency) is 60 feet, when pumping 1,000 gpm at a pump efficiency of 50%,

- Then the extra horsepower required is 30hp (22 kW)

$$hp = (1/0.5) \times 1,000 \text{ gpm} \times 60 \text{ feet} / 3,960$$

$$kW = 0.75 \text{ hp}$$

- If the well is operating for 6 months (4,300 hours)
- => additional consumption of approximately 100,000 kWh
- At \$0.10/kWh, the annual cost due to well losses is:

\$10,000.- / year

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Cost of Good Well Design

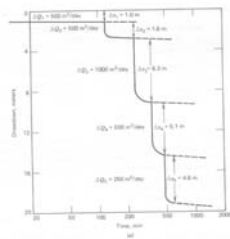
- varies with depth of well
- varies with aquifer material & location of aquifer(s)
- cost for drilling of small diameter test hole (to locate aquifer layers, to determine water quality)
- cost for high-quality, properly sized continuous-slot (wire wrap) screen (extra cost can be saved by locating it opposite productive layers only)
- cost for proper gravel pack material
- cost for proper well development

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Measuring Water Well Losses / Efficiency

Well Efficiency is not the same as Pump Efficiency!

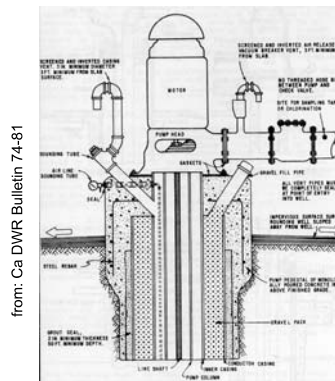


- multistep pump test w/ continuous water level monitoring
- comparison to drawdown in nearby wells (of limited value)
- pump for 1 hour: if water level recovers by 90% within 5 minutes => worst case, unacceptable well losses

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Well Seal and Other Components at the Wellhead



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Water Well Regulations

- ▶ California Well Standards:
 - Bulletin 74-81
 - Bulletin 74-90
- ▶ Includes requirements for abandoning of wells!!
- ▶ County ordinances
- ▶ All wells need to be permitted by county (permit usually obtained by driller)
- ▶ Any drilling operation requires prior notice to USA (usually done by driller)