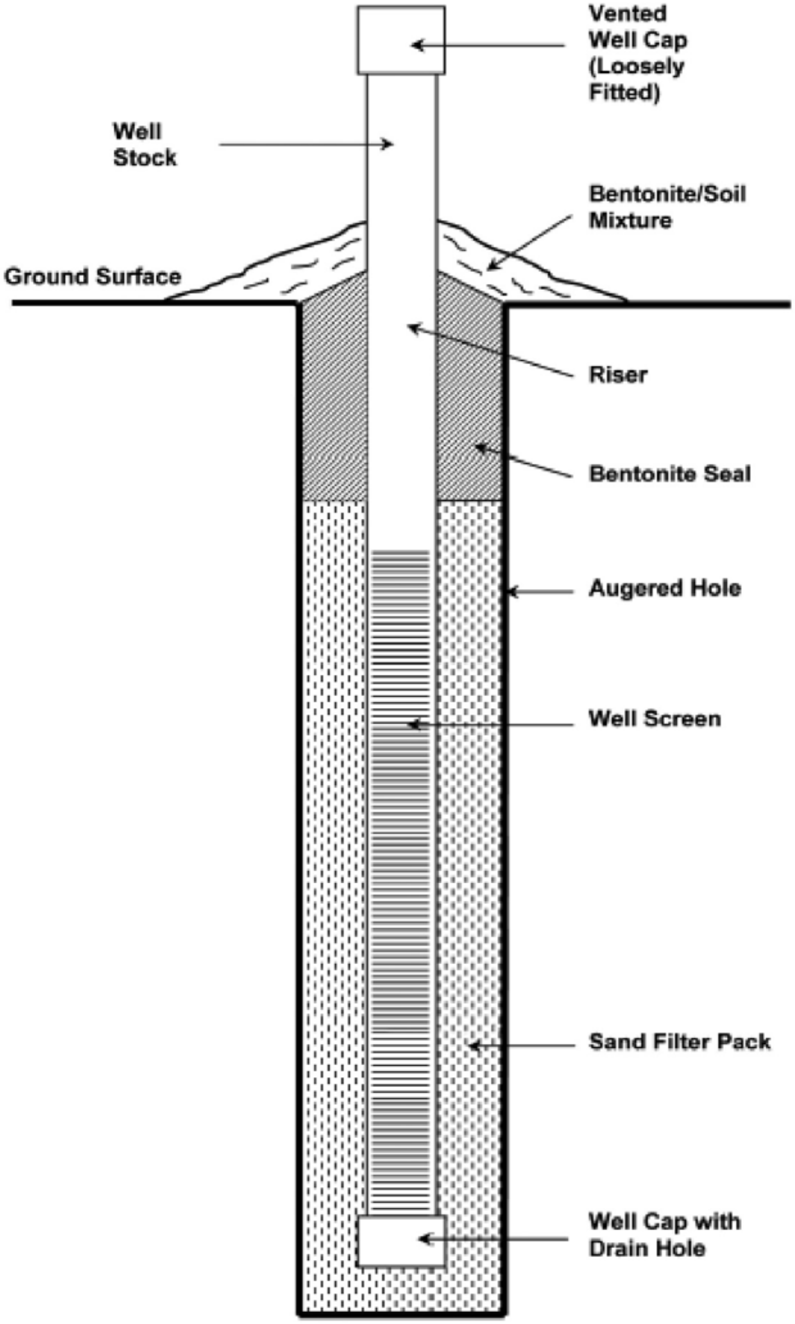
Installing Monitoring Wells in Soils

Version 1.0

August 2008



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Cover Figure: Schematic diagram of a standard design for an installed water-table monitoring well.

Acknowledgements

This technical note is a compilation of concepts and procedures that have been evolving within pedology and Soil Survey for at least three decades. Few of the ideas presented originated with myself. It is an honor to recognize and thank my main teachers concerning these procedures, Lawson Smith (US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, deceased) and Jim Richardson (North Dakota State University and NRCS National Soil Survey Center in Lincoln, Nebraska, retired). It is also a pleasure to thank my fellow traveler and teacher, Wes Miller (NRCS in Texas, retired). Wes' openness, tenacity, and generosity are legendary among those who study soil water regimes. All of us owe him deep gratitude.

I thank Jim Richardson additionally for asking me to compile the discipline's accumulated knowledge and write this technical note for the Service. Participants in the 2007 national meeting of the National Cooperative Soil Survey in Madison, Wisconsin, provided valuable input at the beginning of this effort. I also thank those who took time to review earlier drafts of this document, including those who reviewed anonymously. In particular, I thank Drs. Wayne Skaggs and Mike Vepraskas of North Carolina State University, who provided especially thorough reviews. The insights of all reviewers corrected important oversights and clarified numerous ambiguities.

All errors and omissions in the Technical Note, of course, are my own responsibility. I hope that those who use this Technical Note will suggest needed corrections to the National Soil Survey Center, for incorporation into later versions, including quantitative information on when these procedures can be simplified.

Finally, I thank the National Soil Survey Center for intellectual support and the NRCS in Indiana for allowing me to work on this document.

Steve Sprecher, Ph.D.
August 2008

Foreword

The National Technical Committee for Hydric Soils (NTCHS) has reviewed this document and provided comments to the author. These comments have been considered, and where appropriate, have been incorporated into this work by the author. The NTCHS strongly endorses this document as an important piece of information useful for planning and conducting hydrology studies. It provides scientists with guidance that assist them to adequately plan and conduct investigations that document landscape wetness and the relationships to hydric soil indicators.

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August 2008

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1. PURPOSE

This technical note provides general guidance on how to install and use piezometers and water-table wells to investigate soil water regimes under conditions commonly encountered in Soil Survey and hydropedology studies. Piezometers and water-table wells installed using these procedures act as lined and unlined bore holes, respectively (Soil Survey Division Staff 1993, page 93), usually at depths that desaturate seasonally.

Standard guidelines (Sections 3 and 5) are presented for use in soils where hand augering is practical and saturated hydraulic conductivities are moderate or higher. Alternative methods (Section 6) are provided for problem soils where the standard procedures are impractical or problematic.

Limitations: Procedures described here are appropriate only to monitor changes in water level and hydraulic head. They are not intended for water quality sampling, water supply, or determination of saturated hydraulic conductivity (K_{sat}). Recommended procedures are subject to change as new information and technologies become available.

2. BACKGROUND FUNDAMENTALS

2.1 Terminology. These guidelines employ the following terms and definitions:

1. '**Monitoring wells**' are "well[s] designed for measuring water levels and testing ground-water quality" (US Geological Survey nd). The two kinds of monitoring well discussed in these guidelines are shallow piezometers and water-table wells (Figure 1). When consulting the literature of the various disciplines that use wells, be aware that terminology varies considerably.
2. '**A piezometer'** (Figure 1A) is "an unperforated small-diameter pipe, so designed and [installed] that after it has been driven into the soil the underground water cannot flow freely along the outside of the pipe and can enter it only at the bottom end. The piezometer is so [installed] that its lower end is in the stratum or at the level where the pressure is to be read. The height that water rises above the bottom of the pipe is the pressure head" (from Urquhart, p. 3-4; see also Figure 2). If there is a short length of intake screen below the bottom of the piezometer to prevent sediment migration into the pipe, the depth of hydraulic monitoring in a piezometer is the bottom of the unslotted length of pipe, not the bottom of the intake screen.
3. **'Water-table wells'** are pipes perforated from near the ground surface to the bottom of the pipe (Figure 1B). They "are used to determine the level of the water table. The well permits water to enter the hole at any level, thus connecting the various water bearing strata in the soil profile" (ibid., p. 3-5). The water level recorded inside a water-table well is the elevation of the surface of the groundwater rather than a pressure head at some point within the groundwater deeper than the water-table surface.
4. **'Water'** and '**water flow'** refer to water where pressure head ('piezometeric head') is greater than zero, unless stated otherwise. Monitoring wells do not collect water that is held at soil water pressure heads less than zero (matrix suction).
5. **'Interflow'** is **'**that portion of rainfall that infiltrates into the soil and moves laterally through the upper soil horizons above the water table until intercepted by a stream channel or until it returns to the surface at some point downslope from its point of infiltration' (Soil Science Society of America 2008). Others refer to this as 'throughflow' (Kirkby 1969) and 'subsurface stormflow" (Freeze and Cherry 1979, p. 219).

[Figure 1]

[Figure 2]

2.2. General Principles and Problems. Piezometers and water-table wells are superficially similar but operate in fundamentally different ways (Figure 3). In water-table wells the screened portion of the pipe usually extends above the top of the water table, and the water level within the pipe coincides with the water table in the soil. In contrast, the depth of intake in a piezometer is a single elevation at the bottom of the unperforated pipe, often permanently submerged within the water column. The elevation that water rises in the piezometer is the soil water pressure at that point, not water-table elevation. While adjacent piezometers of different lengths can report different hydraulic heads, nearby water-table wells of different lengths should report the same water-table level.

[Figure 3]

This difference in operation allows use of piezometers and water-table wells in tandem to identify discharge and recharge regimes (Figure 3). When hydraulic heads (water levels above a datum) are the same in piezometers and adjacent water-table wells, vertical gradients are zero and either no flow or slow lateral flow is occurring (Figure 3A). Recharge flow is indicated when either piezometers or the water table indicate the hydraulic head is higher in the surface layers than in deeper layers (Figure 3B). The reverse happens during discharge (Figure 3C). Groups (nests) of two or more piezometers with different intake elevations quantify this information by measuring relative hydraulic heads (in Figure 3, compare Piezometers P3 and P4).

In many soil characterization studies piezometers are used solely to monitor timing and duration of saturation in or below restrictive layers rather than to quantify hydraulic heads and gradients. This is a legitimate use of piezometers but practitioners should not let it blur the distinction between the two instruments.

Soils studies usually use monitoring wells in materials that desaturate frequently and refill from various sources. These highly variable conditions cause design problems that are not encountered when instruments are installed into permanently saturated strata. Major sources of error include bypass-flow and drainage lag time.

By-pass flow occurs when precipitation and run-off waters short-circuit natural infiltration by following preferential flow paths down the annulus around the unslotted riser and/or down large pores to the intake screen (Figure 4). Resulting data indicate an early onset of subsoil response relative to infiltration. If the piezometer was installed in a restrictive layer that remains unsaturated most of the year, the inference of free water at that depth can actually be false (Figure 4B). The most common solution is to seal the annulus with bentonite (Figures 1 and 4A).

[Figure 4]

Drainage lag time. Water-table wells may drain too slowly if installed into low-K_{sat} subsoils (Figure 5). The water level in a monitoring well fluctuates in response to the volume of water released from or to the soil. The well and its sand pack act as a reservoir, and there can be a considerable lag time while the relatively large volume of water in the well equilibrates with the network of small-diameter pores in the soil. Drainage lag times are more problematic when the well is installed into horizons with low or very low K_{sat}, such as in high clay soils (e.g., Vertisols, some argillic horizons, and dense glacial till).

[Figure 5]

One solution to these problems of by-pass flow and drainage lag time is to shorten the length of intake screen and reduce the diameter of wells or piezometers. Wells should not extend into low or very low K_{sat}

horizons where lag times will be significant. Deep wells should be unslotted and sealed with bentonite through shallow horizons to prevent bypass flow.

3. STANDARD DESIGN RECOMMENDATIONS

3.1. Instrument Design. Soils studies employ monitoring wells in a variety of settings. Table 1 presents the most common settings and appropriate instruments. Problem situations described in Section 6 may require special designs.

[Table 1]

Figure 1 provides standard recommendations that can be modified per site-specific needs. General rules to follow are:

1. For water-table wells, install well screen through subsoil horizons where water tables are expected to fluctuate.
2. Install unslotted riser sealed with bentonite through upper horizons that likely carry interflow, such as Ap, A, and E horizons, horizons with platy structure or tillage pans, and some lithologic discontinuities. A 30-cm long unslotted riser should work in many cases (Figure 1).
3. Do not install water-table wells into restrictive layers or layers with K_{sat} significantly lower than in the overlying layer. Use piezometers instead.
4. Install water-table wells no deeper than study objectives require. Short wells may be required to monitor very shallow saturation regimes, such as in episaturated clays.

3.2. Study Design. Collect hydrology information and refine study questions before designing individual wells. For map unit characterization studies, locate wells where both morphology and hydrology are representative of the subject soil series or component. Avoid soil boundaries, inclusions, topographic anomalies, and artificial drainage. Describe soils for each well, including field estimates of K_{sat} (Soil Survey Division Staff, 1993, p. 107+).

To find sites with representative hydrology make a qualitative landscape model of above-ground and below-ground water-flow paths to and from the soil of interest. Likely flow paths following a precipitation event include depression storage, run-off, interflow, infiltration, and groundwater flow (Figure 6; e.g., Kirkby 1969; Freeze and Cherry 1979; Richardson et al. 2001). If available, gather pre-existing hydrologic information such as well logs, flood plain maps, stream gauge data and analyses, and drainage maps.

[Figure 6]

Decide which horizons to monitor by comparing study objectives, soil profile descriptions, and landscape models. Identify those depths that will be served by a single water-table well and those depths that will require piezometers. Design water-table wells no deeper than necessary to gather desired information.

In theory, a minimum of three piezometers is required to determine water-flow direction in a two-dimensional plane. In practice, more are usually needed because of soil and geologic heterogeneity. Direction of water flow may change seasonally. More instruments may have to be installed as results come in and are analyzed.

Wetlands. Wetland hydrology studies often require knowledge of legal wetland definitions. Consult personnel with appropriate experience and authority. Legal hydrology criteria are often tested using 12- to 15-inch deep monitoring wells (Figure 7; National Technical Committee for Hydric Soils nd; US Army

Corps of Engineers 2005). Use of such shallow wells addresses regulations implementing the Federal Clean Water Act and reduces uncertainty about bypass flow and lag-time at depths critical for wetland definitions.

Avoid installation in microtopographic highs and lows if water level data will be interpreted to within a few centimeters or less. Data should be collected daily during critical seasons.

Deeper instruments should also be installed to gather information about whole-profile water regimes and water flows contributing to the hydrology of the wetland system, especially if the wetlands will be managed, restored, or enhanced after the study has been completed (Noble 2006). Shallow wells alone do not supply any information other than whether legal wetland definitions are met.

[Figure 7]

4. CONSTRUCTION

4.1. Well Stock. For the standard design, monitoring wells should be made with commercially manufactured well stock, usually with schedule 40 PVC pipe. Use the smallest diameter well stock that will accommodate your recording instruments. Automatic pressure transducers commonly require 2-inch diameter pipes. Some commercial sources carry smaller diameter sensors and recorders. Well stock greater than 2 inches in diameter is not recommended; 1-inch ID pipe or smaller is preferred if you have the option.

4.2. Riser. The riser is the unslotted pipe that extends from above ground to the top of the well screen below ground (Figure 1). The riser should extend far enough above ground to allow easy access but not so high that the leverage of normal handling will break below-ground seals; a 30-cm length is commonly used. The riser needs to be vented and fitted with a removable cap (Section 4.6).

Except for very shallow wells, an unslotted riser should extend below ground through Ap, A and E, or similar horizons with high horizontal K_{sat}. The Illinois Geological Survey has minimized interception of interflow in their landscapes with a standard design of a 45-cm depth of riser and 30 cm of bentonite to the sand pack (Miner and Simon 1997).

4.3. Well screen and Well Point. The intake is the portion of the pipe designed to allow entry and exit of soil water. Most studies use commercial well-screen with 0.010-inch-wide slots (Figure 1). Construct well screen by drilling holes in unslotted pipe only if commercially milled stock is unsuited to your study. A cap at the bottom of a screened pipe prevents material from sloughing in from beneath. Construct piezometers with the open, unprotected bottom of the pipe as the water intake only if soil migration will not occur (e.g., Section 6 – Stony Soils, and Reeve 1986).

Commercial well screen often has a length of unslotted pipe and joint or threads below the screen, designed either to connect to further lengths of screen or to a well point. Such well points act as reservoirs where free water remains trapped after the adjacent soil desaturates. The well-point may also protrude into an underlying horizon that should be left undisturbed. To avoid these problems, cut commercial well screen to the desired length within the slotted portion of the stock (Figure 8). Glue a PVC cap at the bottom of the screen and drill a small vent hole in the bottom cap.

[Figure 8]

If it is necessary to construct well screen in-house, drill approximately 36 0.25-inch diameter holes evenly spaced over the bottom 6-inches of pipe to provide an intake area comparable to that of commercially milled screen.

If study purposes require a short lag time, minimize the volume of water reserved in the standpipe and sand-pack and maximize the surface area for water intake/outflow. Well volume can be reduced by using well stock with a small interior diameter and a small annulus; surface area can be increased by using a long perforated screen and thick-walled well-stock. Hanschke and Baird (2001) provide design recommendations appropriate for quantitative hydrologic studies.

4.4. Filter Pack and Filter Cloth. The filter pack is the sand placed in the annulus around the well screen. It protects the screen from plugging and promotes water movement via a hydraulic gradient from the denser soil to the well screen.

Clean silica sand is available from water-well supply houses in uniformly graded sizes. Sand that passes a 20-mesh screen and is retained by a 40-mesh screen (20-40 sand) is recommended with 0.010-inch slots. In most sandy soils, natural sand removed from the auger hole may be repacked as a filter pack.

In problem soils (Section 6) filter socks may have to be substituted for sand packs. Filter socks are available from engineering and water-well supply houses. They can be constructed in-house from geotextile fabric and have been successfully attached to the riser with epoxy cement or water-proof tape. Attach the filter cloth tightly enough that it will not tear off the pipe during driving through soft sediments. Experiment with the strongest epoxy and cable ties you can find. Pipes protected with filter fabric should be checked for clogging on a regular basis; they can clog with the dispersive fines in some of these soils, and bacterial mats frequently grow on filter textiles.

Soil water moves between the stand pipe and the soil by way of the filter pack rather than directly into and out of the well screen. An overfilled filter pack lengthens the zone of soil intercepted for monitoring and increases well response time due to increased reservoir volume.

4.5. Bentonite Seal. In most soils the annulus around the unslotted portion of the riser is filled with a bentonite plug that extends from the soil surface to the filter pack below. This protective plug minimizes surface water running down the riser and, in piezometers, minimizes bypass flow through macro-cracks that intercept the riser above (Figure 1). A mound of soil mixed with bentonite is shaped at the ground surface so water will not pond around the riser.

Bentonite is available from well-drilling supply companies in powder, chip, or pellet form. Chips are easiest to use in the field. It is almost impossible to manipulate wet bentonite satisfactorily, so try to install instruments requiring bentonite plugs when soil water tables are low.

Grout. ASTM D-5092-04 (2004) and others following ASTM standards (e.g., Young 2002) recommend grout as the sealant in the annulus around wells. They discourage the use of bentonite near the ground surface where it may dry out and crack (Driscoll 1986). Nevertheless, most pedologists have found bentonite to be superior to grout for monitoring wells at depths and bore-hole diameters appropriate to soil survey. Bentonite is easier to handle when installing and dismantling study sites. In Soil Survey studies it has been found to swell shut quickly upon onset of rain storms and prevent bypass flow adequately. Bentonite also allows the well to be re-used at a new location. Grout may be appropriate for wells that are intended to be permanent and not moved.

4.6. Well Cap. Well caps protect pipes from contamination and rainfall. Most automatic recording devices include their own well cap.

If manual recording is required, select or make a cap that can be removed and replaced easily at each reading. Tight-fitted caps (threaded or unthreaded) may seize to the riser and require rough handling to remove, thereby compromising the underground seal. Either the riser or the well cap should be vented to allow equilibration with outside air pressure. Well caps should be made of materials that will not deteriorate in sunlight or frost. Caps can be made quickly and inexpensively from PVC stock using the design shown in Figure 9.

[Figure 9]

4.7. Water Level Reading Equipment. The preferred method to monitor water levels is with automatic recording devices. The most commonly used instruments are down-well transducers or capacitance-based sensors. Purchase devices with the ability to compensate internally for variations in barometric pressure. Follow manufacturers' instructions when using automated water level recorders.

The credibility of monitoring data is enhanced by the high frequency of readings allowed by automatic devices. These devices may be reused for several projects, so cost estimates should be prorated over their expected life rather than assigned to a single study. Automatic recorders are usually less expensive than travel costs and salaries if study objectives require frequent readings at remote sites.

Check for instrument failure at intervals no longer than you can tolerate data gaps. This may be more frequent during critical seasons such as spring draw-down. Be sure to read and follow manufacturers' instructions for maintenance and quality assurance. Height of the riser above the ground surface should be noted when data are downloaded. Check instrument calibration periodically with manual water-table measurements, and check for clogging with the pump test as local experience dictates.

Measure water levels manually with either a commercial water-level sensor or a steel measuring tape marked with carpenter's chalk or a water-soluble marker.

For manual readings, Morgan and Stolt (2004) identified the maximum height of high water-table fluctuations that occur between site visits by using a float and a movable magnet on a steel rod within the standpipe (Figure 10). Using logger data, they created templates of water-level response to precipitation events for their different soils. Float-data and precipitation records can thereby serve as surrogates for well-logger data for studies with several wells at a site but only a few continuous recording devices.

[Figure 10]

5. STANDARD INSTALLATION

Bore holes are generally hand-augered. To provide a 2-cm annulus in which to drop and tamp sand and bentonite, auger ~5 cm wider than the well stock. Install tubes into dry holes whenever feasible.

5.1. Equipment List.

1. Piezometer or well
2. Bucket auger: ~5 cm wider than the OD of the pipe being installed, with auger extensions
3. Water level reading instrument
4. Wire brush to break up smeared soil walls, if soil conditions require
5. Tamping tool (lengths of PVC pipe cut in half longitudinally have been used successfully)
6. Method to mark depths temporarily on the tamping tool, such as duct tape
7. Bentonite chips
8. Commercial grade silica sand

9. Steel tape long enough to measure the longest pipe
10. Paint marker to label pipes; paint lasts longer than permanent marking ink
11. 5-gallon bucket
12. Water sufficient to test pipes for plugging
13. Hand pump or bailer sufficient to empty deepest pipe
14. Survey equipment of sufficient accuracy to measure elevations required for study purposes. Not all studies require comparative elevation data.
15. Soil description equipment
16. Documentation forms

5.2. Piezometer Installation.

1. Auger a hole in the ground with a bucket auger ~5 cm wider than the well stock to a depth approximately 2 cm deeper than the bottom of the piezometer. Be sure the auger hole is vertical.
2. Scarify the sides of the auger hole over the area to be screened, if smeared during augering.
3. Place ~2 cm of clean sand in the bottom of the hole.
4. Insert the piezometer into the hole but not through the sand.
5. Pour and gently tamp more of the same sand in the annular space around the screen and 2 to 4 cm above. Be careful not to overfill with sand. The depth of tamping for each well can be marked on the side of the tamping tool with a piece of tape.
6. Pour and gently tamp bentonite chips above the sand to the ground surface.
7. Make a mound of soil and dry bentonite around the riser at the ground surface, shaped to prevent puddling around the base of the riser. Moisten before leaving.
8. Check for clogging (Section 5.4). Reinstall and recheck if necessary.
9. Mark the side of the riser with paint at the top of the mounded soil/bentonite mixture and label the well.
10. Record height of well above ground surface and document installation.
11. Install and calibrate any water-level recording instruments.

5.3. Water-table Well Installation. Installation of a water-table well entails the same steps as above, with the modification that the filter pack extends the entire length of the well screen.

5.4. Checking for Clogged Pipes. After installation, check intake response by either pumping or adding water. The volume of water added depends on K_{sat}. Water levels should return at approximately the same rate as they would in freshly dug holes without any pipe. If the water does not return to the pre-pumped level within the expected time, try to develop the sand pack per Section 5.5 below. If this fails, remove the instrument and determine why it is plugged. Check for plugging every few months because wells can plug due to bacterial growth or migration of fines.

5.5. Well Development. Well development is a standard practice used during installation of water supply wells (e.g., Driscoll 1986) and occasionally is appropriate for monitoring wells, too. The procedures are intended (1) to repair damage done to borehole walls during augering, (2) to minimize sedimentation of fines through the filter pack, and (3) to improve hydraulic characteristics of the filter pack and its interface with the borehole wall.

To develop a monitoring well, pump water out of the pipe until it is clear. The more aggressive commercial procedures for supply wells (over-pumping with high volume pumps and backwashing with high pressure surge blocks) are probably inappropriate for shallow pedology studies. Many of the benefits of well development can be obtained by installation when soils are dry to bore-hole depths. Nevertheless, even water-table wells should be checked for clogging and sediment accumulation, and pumped clean when necessary.

5.6. Site Considerations.

Elevations. When hydrologic gradients are to be calculated it is necessary to measure relative elevations of all instruments that will be compared to each other. Survey relative pipe elevations to the accuracy needed for the study. Well readings in nested instruments are only as accurate as the measurements of relative pipe elevations. Resurvey all instruments whenever there is evidence of seasonal pipe movement. Note all changes in elevation in documentation forms, computer spreadsheet programs, and meta-data notes.

Pipes can move upward several centimeters during cycles of wetting/drying and freezing/thawing. Note that the ground elevation itself may rise and fall in Vertisols.

Foot Traffic. Some researchers have found it necessary to install boardwalks around instruments to protect surface soil integrity, especially during wet seasons.

Concrete Pads. Some localities require concrete pads around wells. Local regulations should be observed at all sites.

Site Disturbance. Protection measures may be necessary if disturbance from animals or vandalism are problems. As appropriate, fences or locked, steel casing in cement or grout may be necessary (Miller and Bragg 2007; Young 2002), or bring replacement parts on site visits.

6. PROBLEM SOILS

Standard procedures may not be adequate when manual augering is impractical, such as in stony or rocky soils; semi-permanently saturated sands, silts, or organic soils; soils with low or very low K_{sat}; or soils with high shrink-swell properties. Modifications to the standard procedures are appropriate whenever local conditions require changes. The guidelines in this Section are less specific than the standard procedures because local conditions usually require site-specific modifications.

6.1. Sandy soils. Plugged well screen is not a problem in most sandy soils, so filter packs are rarely necessary. Use a filter cloth if experience shows that screens plug or pipes fill with sediment. Bentonite seals may be dispensed with as most sands will collapse about the riser after augering. Bore holes can be re-filled with the sand removed during augering.

Drive well pipes if soil collapses while augering. Sandy soils are often soft enough that commercial PVC well stock and well points can be used. Drill drain-holes in the sides and bottom of well points to minimize water storage. Wells can be vibrated or jetted into wet, unconsolidated sands (Reeve 1986). See Section 6.4 for installation alternatives.

6.2. Soft Silts and Histosols. Histosols and alluvial silts that desaturate seasonally may need to be monitored with water-table wells over the upper meter and with piezometers at greater depths.

These soils usually are soft enough to drive PVC well stock into but too soft for sand packs and bentonite plugs. Use filter socks rather than sand packs.

The method of installation will depend on viscosity of the material. The objective is to minimize soil disturbance and encourage natural sloughing around the pipe. Driving is preferred if the filter cloth doesn’t tear off. It may be necessary to auger a pilot hole with a narrow screw auger first. If the pipe can be driven while the soil is saturated, the matrix will probably slough around the pipe and the well will function properly.

Silts and organic soils may smear considerably during installation with either driving or augering. Abrade bore-hole walls with a wire brush (Miller and Bragg 2007) and/or pump the well until water flows freely (Section 5.5; Baird et al. 2004). Baird et al. (2004) provide a very useful review of experience applicable to use of piezometers in wetlands, including peraquic silty and organic soils.

6.3. Soils with High Shrink-Swell Properties. High shrink-swell soils present numerous problems for study design. Water regimes are episaturated and become progressively drier with depth, with the exception of occasional pockets of saturation down closed cracks. Episaturated regimes vary from microhighs to microlows. Deep-profile saturation occurs transiently in cracks but penetrates only slowly into the matrix between cracks. In some Vertisols it has been shown that deep cracks are organized into a "chimney and bowl" pattern (Figure 11; Miller and Bragg 2007), where intersecting vertical cracks push soil upward to form the microhighs, with microlows in-between over the bowls.

[Figure 11]

Depending on study objectives, water regime studies may need to include methods to monitor matrix and gravimetric water contents as well as free water regimes. Periodic physical sampling may be required. Instrument selection is dictated by K_{sat}. If study objectives require characterization of the regime of episaturation, install shallow water-table wells no deeper than the depth of episaturation, similar to those used for wetland regulatory studies (Section 3.2, Figure 7; Miller and Bragg 2007). Monitor water regimes separately in contiguous microhighs and microlows.

Piezometers should be used below the surface layer, rather than water-table wells. Deeper piezometers should be installed under microhighs and microlows in nests with the shallow wells.

1. **Bypass flow:** The major installation problem for piezometers in high shrink-swell soils is to avoid bypass flow along riser walls. The surface area of the filter pack should be kept small in order to reduce the likelihood of being intercepted by desiccation cracks. The entire length of unslotted pipe below ground should be sealed with bentonite. Some researchers have constructed piezometers with only 2.5cm of slotted well screen and 7 cm. of filter pack (2 cm above and 2 cm below the screen). Instruments should be replicated at least 3 times at each depth. Soil should be sampled periodically for gravimetric water content to check the validity of piezometer readings. Tensiometers may help interpret well data, but they can experience bypass flow, too, and therefore need to be installed with bentonite sleeves.

2. **Lag time for piezometer response:** These low K_{sat} soils change water content slowly except for ephemeral pipe-flow down cracks at the beginning of the rainy season. Piezometers that fill with free water intersected from a crack may hold that water longer than the surrounding soil. Interior volumes of piezometers need to be as small as practical. Porous ceramic cups have been used as intake ports for piezometers, similar to tensiometers (Wayne Hudnall, Texas Tech. Univ., Lubbock TX, personal communication, June 2007). This eliminates the need for a sand pack. In conjunction with narrow-ID well stock, it reduces the volume of water that has to respond to moisture changes in these very-slowly permeable soils.

3. **Pipe movement:** The shrink-swell action of these soils may pull pipes out of the ground several centimeters in the rainy season. Amount of movement varies and may be more extensive in shallower pipes (Miller and Bragg 2007).

6.4. Stony Soils. Very stony soils do not allow hand augering of bore holes for installation of PVC well stock. Two successful alternatives are drilling bore holes with engine-powered equipment and driving steel well stock into rocky soil.

Drilling requires a drill rig and access to the site. Power probes for Soil Survey have been fitted with bits and operated at very slow speeds to penetrate rock. Once a bore hole has been drilled out, PVC well stock can be installed using filter packs and bentonite plugs per the standard guidelines. Disadvantages are cost, time, site access, and need for operator experience. The principle advantage is that commercially milled PVC well stock can be used along with filter packs and bentonite plugs. Well drilling is discussed in US Geological Survey documents, such as Shuter and Teasdale (1989).

Driven Wells: Several of the problem soils require that well stock be driven into the ground, often with sledge hammers and/or fence post drivers. The necessary steel wells have usually been constructed in-house, although some commercially manufactured wells are designed for manual driving. Well design will depend on the nature of the soil, the depth and seasonality of the aquifer being monitored, and the requirements of water-level recorders.

Wells driven into stony ground are not protected against bypass flow (Young, 2002) because bentonite plugs are not practical. The quantitative significance of water levels in such wells depends on the nature of the horizons intercepted. If runoff and interflow are significant and soil conditions are appropriate, the surface horizon(s) may be excavated manually for installation of a bentonite plug.

Two different approaches are commonly used when driving wells into hard soil: (1) the well stock itself is strong enough to be driven directly into the ground (Figure 12A), or (2) a drive-rod is placed inside the well stock and receives the bulk of the pressure from the hammer and soil (Figure 12B and 12C). In both cases a steel hammer cap is constructed so that the pipe does not receive blows directly.

[Figure 12]

Wells driven directly require a hardened drive-point to penetrate the rocky soil. Reeve (1986) inserted a large rivet in the bottom end of the pipe as a drive-point (Figure 12A). After driving the well into the soil, he pushed the rivet out with a narrower “punch-out rod” and flushed a cavity at the base of the pipe. The open end of the pipe and cavity flushed out below served as the intake zone.

Geist et al (1998) welded a conical steel point onto the end of the pipe; the driven well-point pulls the standpipe behind it as the drive-rod is pounded downward (Figure 12B). The well screen was made by drilling ⅛-inch to 3/16-inch holes over 12 inches of pipe. It is necessary to pump or blow sediment out of the drill holes of these pipes after installation.

Baxter et al. (2003) used a drive-rod and drive-cap to force steel well-casing into rocky stream beds (Figure 12C). They then pulled out the drive-rod, inserted a small-diameter PVC piezometer into the casing and pulled the casing out, leaving the PVC piezometer in the stream bed. The well-point was incorporated into the design of the drive-rod so that the well-casing was free to be extracted. The steel well-casing and drive-rod could be used multiple times for installation of numerous PVC wells.

7. DOCUMENTATION

7.1. Study Site Data. NRCS studies should follow agency data-quality and recording protocols. Water level data are nearly meaningless to others without adequate metadata. At a minimum, metadata should include (1) study objectives, (2) study and instrument locations, (3) times data were collected and downloaded, (4) standard soil descriptions, instrument characteristics, and installation methods, and (5) maintenance events such as recalibration of pressure transducers or changes in elevation. Figure 13 is an example of a metadata record, which includes details of monitoring well installation and soil characteristics that are shown graphically at the same scale.

[Figure 13]

Presentation of well data (e.g., water-level fluctuations) should include soil profile information at the same scale for easy comparison. Also, it will make it easier to compare other pertinent trends with the well data. Figure 14 is an example of the graphic display of well data with a superimposed soil profile and stacked graphs of concurrent meteorological and soil-chemistry data.

[Figure 14]

7.2. Meteorological Data. Meteorology records should accompany hydrology data. Precipitation data are often displayed graphically on the same temporal axis as recorded water levels (Figure 14).

Rainfall data: Automatic recording rain gauges should be installed if budgets allow. Otherwise, precipitation data should be collected from the nearest weather stations. Estimates of rainfall can be interpolated between rain gauges using methods described in the National Engineering Handbook, Part 630, Chapter 4 (NRCS 1993).

Onsite recording rain gauges are critical when quantitative water budgets are to be calculated or antecedent water-table regimes are to be modeled from historic meteorological data. Automatic rain gauges fail frequently enough that manual rain gauges should be installed with them so data-gaps can be filled.

Antecedent precipitation: Precipitation data are more useful if they can be compared to long-term records for particular recording stations (for example, climatology statistics often use the most recent 3 decades as a standard reference period for comparisons). These analyses are available from several Internet websites (below). To smooth out anomalies inherent in spatial heterogeneity, regional climatology data are often reported for climate divisions, which usually are meteorologically similar areas within a state.

The NRCS's Hydrology Tools for Wetland Delineation (Bullet 1 below) includes a method for evaluating whether the preceding three months of precipitation were drier than normal, within the range of normal, or wetter than normal. It uses climatic analyses of the WETS Tables (Bullet 2 below). These two analyses provide information only for the preceding three months of precipitation and should be supplemented with evaluations of longer-term climatic trends, such as those available in the Palmer Drought Indices (Bullet 3 below), and the Standardized Precipitation Index (Bullet 4 below). Recent and historic precipitation data are usually available online through the various State Climatologists' offices (Bullet 5 below).

1. NRCS. 1997. Hydrology Tools for Wetland Delineation (Engineering Field Handbook Part 650, Chapter 19) Provides method to calculate whether preceding 3 months of precipitation were within the range of normal, using data from the WETS Tables (Section 7.2.2. below)

2. National Water and Climate Center. nd. WETS Tables. http://www.wcc.nrcs.usda.gov/climate/wetlands.html. Tables of likelihood (30th & 70th percentile) and mean precipitation for most official weather stations in the nation, based on previous 3 decades of data.

3. National Weather Service. nd. Palmer Drought Indices. http://www.cpc.ncep.noaa.gov/products/site_index.shtml Analyses of drought and surfeit precipitation and evapotranspiration for climatic divisions, including past decade of historical data, updated weekly. Indices are not statistically standardized.

4. Western Regional Climate Center. nd. Standardized Precipitation Index. http://www.wrcc.dri.edu/spi/spi.html. Precipitation percentiles for climatic divisions of the nation, calculated for time periods of 1 to 72 months of antecedent precipitation.

5. American Association of State Climatologists. nd. State Climate Offices. http://www.stateclimate.org/. Sources of precipitation data, statistical analyses, and professional assistance.

Normal precipitation: The frequency distribution for precipitation is not a bell curve, so 50th percentile (median) precipitation is not average precipitation. The meaning of 'normal precipitation' varies with context and institution. The National Weather Service uses 'normal' to mean the arithmetic average. The National Water and Climate Center has defined 'normal' to be the range of precipitation likelihoods between the 30th and 70th percentiles. 'Normal' for the Palmer Drought Indices is not statistically defined and varies between climatic divisions. Soil Taxonomy has a discussion and definition of 'Normal Years' in the section on soil moisture regimes. Check terminology when using unfamiliar climatic analyses.

8. RESEARCH NEEDS

Soil science has been using monitoring wells for decades but there is surprisingly little research on instrument design in soils that desaturate seasonally. Few disciplines monitor water-level fluctuations in formations as shallow and dynamic as soils, and those that do usually study aquifers that rarely dry out. The physical monitoring setting for soils presents unique challenges. Several questions need further investigation.

1. Is there a threshold K_{sat} below which water-table wells should be replaced with piezometers?
2. What is the optimum method to study soils with significant shrink-swell behavior? Some fundamental problems are
    a. Are there better ways to minimize by-pass flow down vertic cracks?
    b. How do we optimize instrument response in low-K_{sat} clays?
    c. Are there other instruments that are better suited for these soils?
    d. What are appropriate replication rates?
3. When should we use grout instead of bentonite? ASTM standards and the well-drilling industry recommend grout.
4. What other recording instruments are suitable for pedology research but under-utilized in the discipline? Possible alternatives include modified tensiometers (Michael Vepraskas and Wayne Skaggs, personal communications, April 2008) and closed hydraulic piezometers (mentioned by Hanschke and Baird 2001).
5. Are recording instruments available that will allow us to use smaller diameter well stock?
6. What is the appropriate design for well screens constructed in-house with drilled holes?
7. Can we develop a standardized method for manual driving into rocky soils?
8. When can we dispense with well screens, sand packs and filter cloths? Perhaps the standard piezometer installation in many soils could simply be a length of open-ended EMT pipe driven a few centimeters into the bottom of an oversized bore hole and sealed with bentonite, with the water-entry port augered out the bottom of the pipe with an undersized screw auger.

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Table 1. Appropriate instruments to study soil free-water regimes

	Study Objectives				
Nature of water regime[*]	Water-table elevations	Presence of free water at specific depths	Vertical water flow direction	Quantitative pressure heads	Landscape water flow paths
Unconfined water regime (high K_{sat}) [**]	Well[†] slotted over depths of water fluctuation.	Well and piezometers	Well and piezometer or 2 piezometers	Piezometers	Piezometers
Unconfined water regime (low K_{sat})[‡]	Piezometers and shallow wells	Piezometers	2 piezometers	Piezometers	Piezometers
Mixed (perched water tables)	Well above restrictive layer and piezometer(s) within restrictive layer	Well above restrictive layer and piezometer(s) within restrictive layer	Piezometers	Piezometers	Piezometers
Confined water regime	Piezometers in water-bearing layer and in confining layers above and below	Piezometers	2 piezometers	Piezometers	Piezometers

[*] Unconfined water regimes occur where there are no restrictive layers higher in the profile (apparent water table). Confined water regimes have an overlying restrictive layer (artesian water).

[**] ‘High K_{sat}’ means saturated hydraulic conductivity class that is moderately high or higher.

[†] ‘Well’ means water-table well in this Table.

[‡] ‘Low K_{sat}’ means saturated hydraulic conductivity class that is moderately low or lower. This also includes restrictive layers.

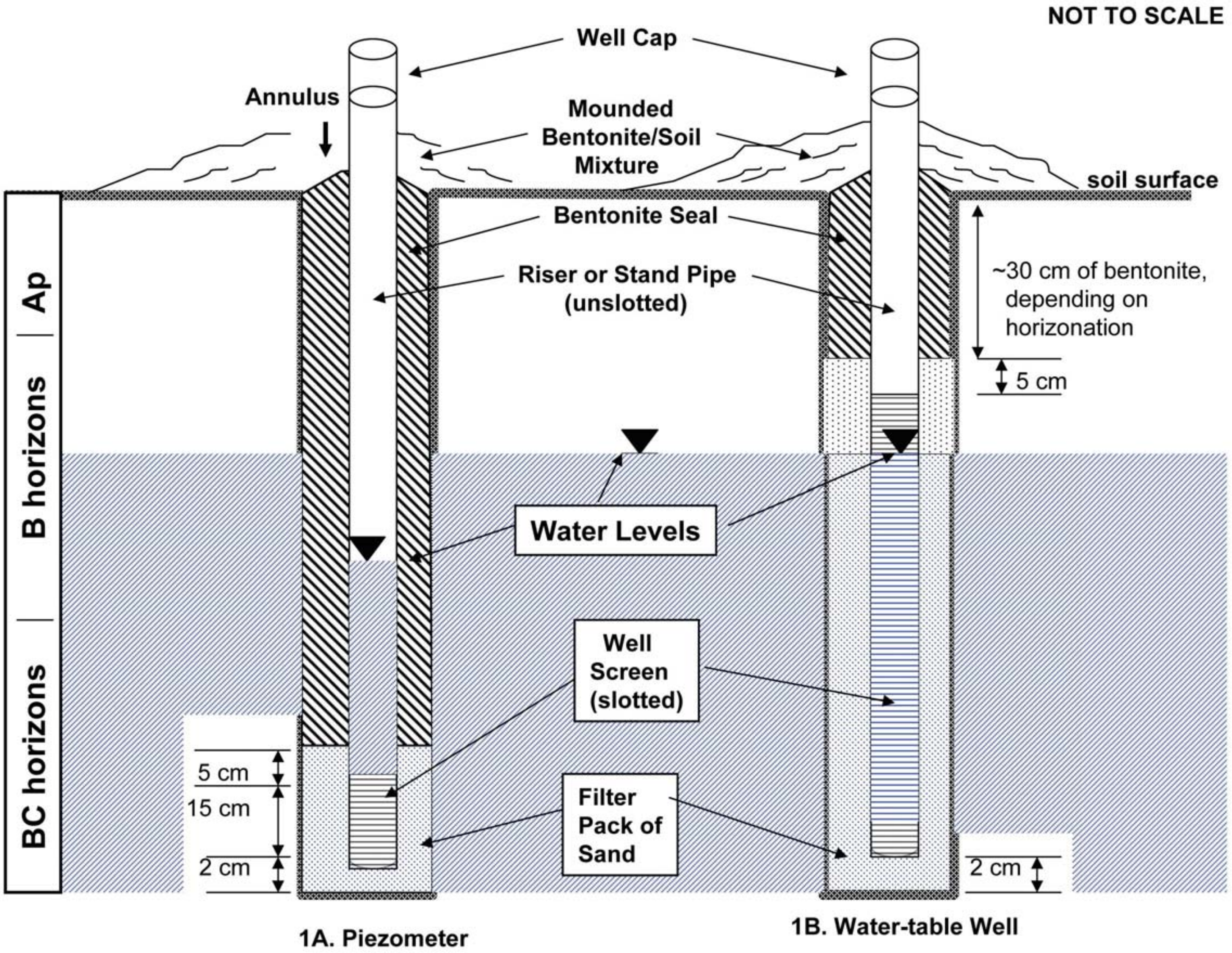


Figure 1. Standard installations for soil studies of **(1A)** a piezometer and **(1B)** a water-table well.

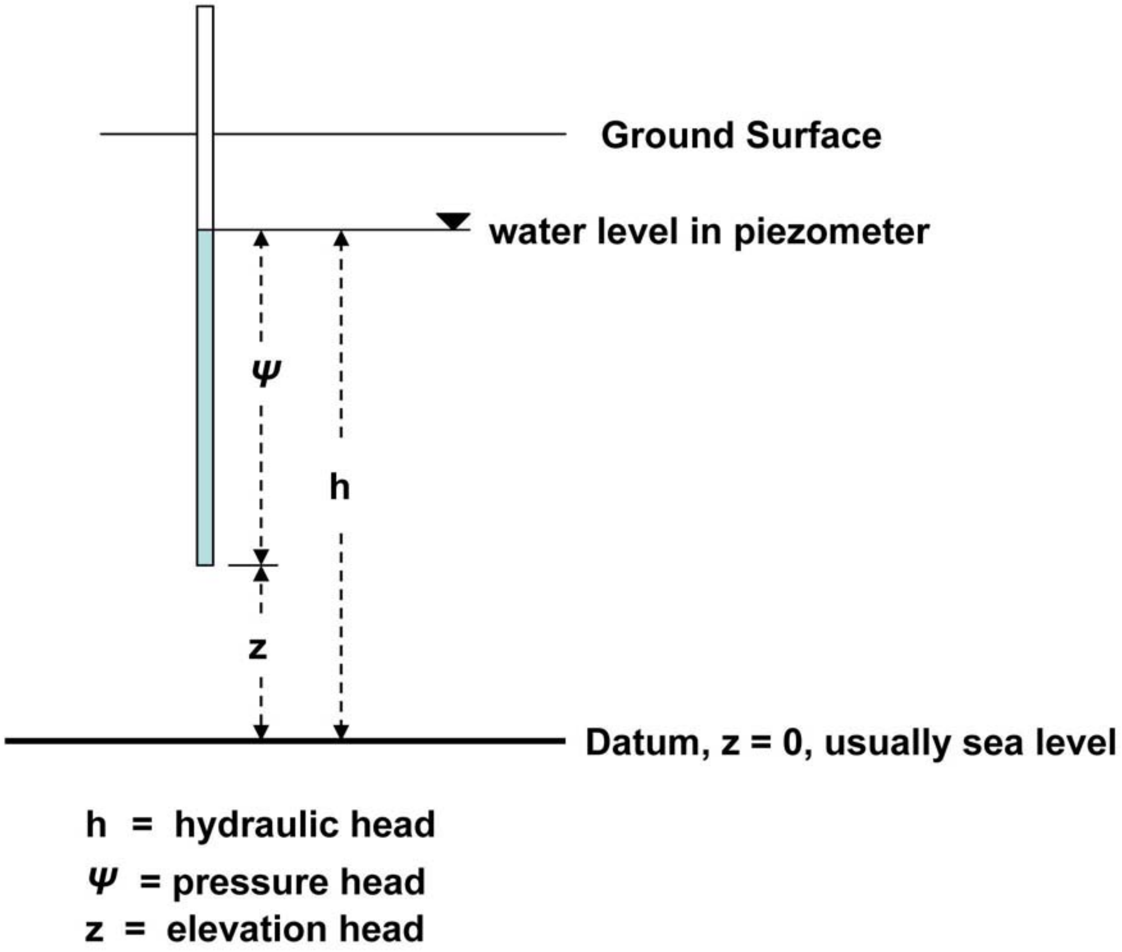


Figure 2. Hydraulic head h, pressure head Ψ, and elevation head z (usually sea level).

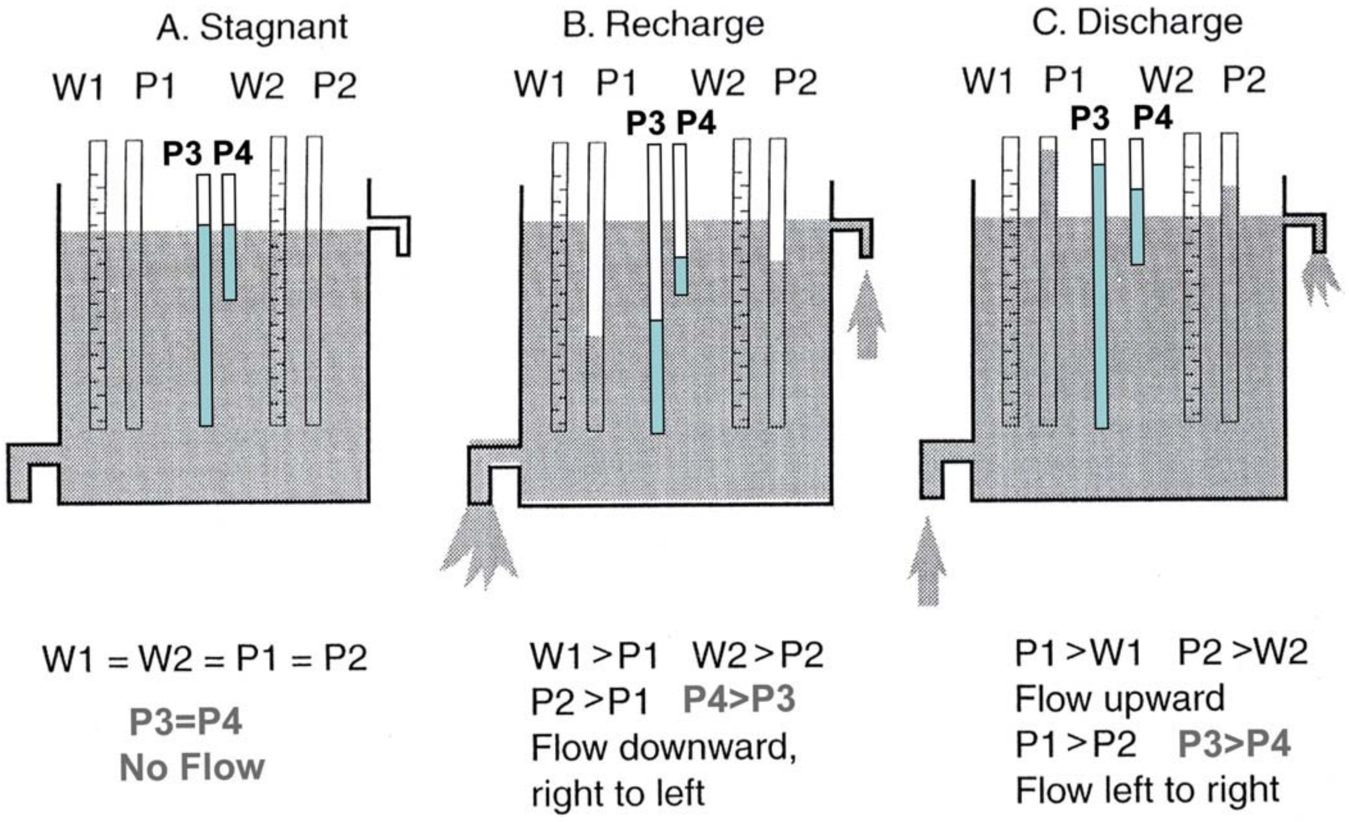


Figure 3. Schematic diagrams of water-table wells (W) and piezometers (P) demonstrating different water-level responses in different instruments. Water flows in tanks differ both laterally and vertically. Instrument pairs 1 vs 2 demonstrate contrasting measurements in instruments of the same length but spaced apart laterally. Instrument pairs P3 vs P4 demonstrate contrasting measurements of piezometers of different lengths located adjacent to each other. **(3A)** In **stagnant water** no head gradients exist, so water levels are the same in all piezometers and wells. **(3B)** In **recharge systems** water flows vertically downward to recharge the groundwater, so shallow P4 intercepts a higher hydraulic head than deeper P3. P1 and P2 pick up the lateral head difference from right to left as well as the vertical difference. **(3C)** In **discharge systems** water flows upward and discharges toward the land surface. Hydraulic gradients and instrument relationships are the reverse of those in recharge system 2B. In all three cases (A, B, and C) water levels are the same in water-table wells. Figure modified from Richardson et al. (2001).

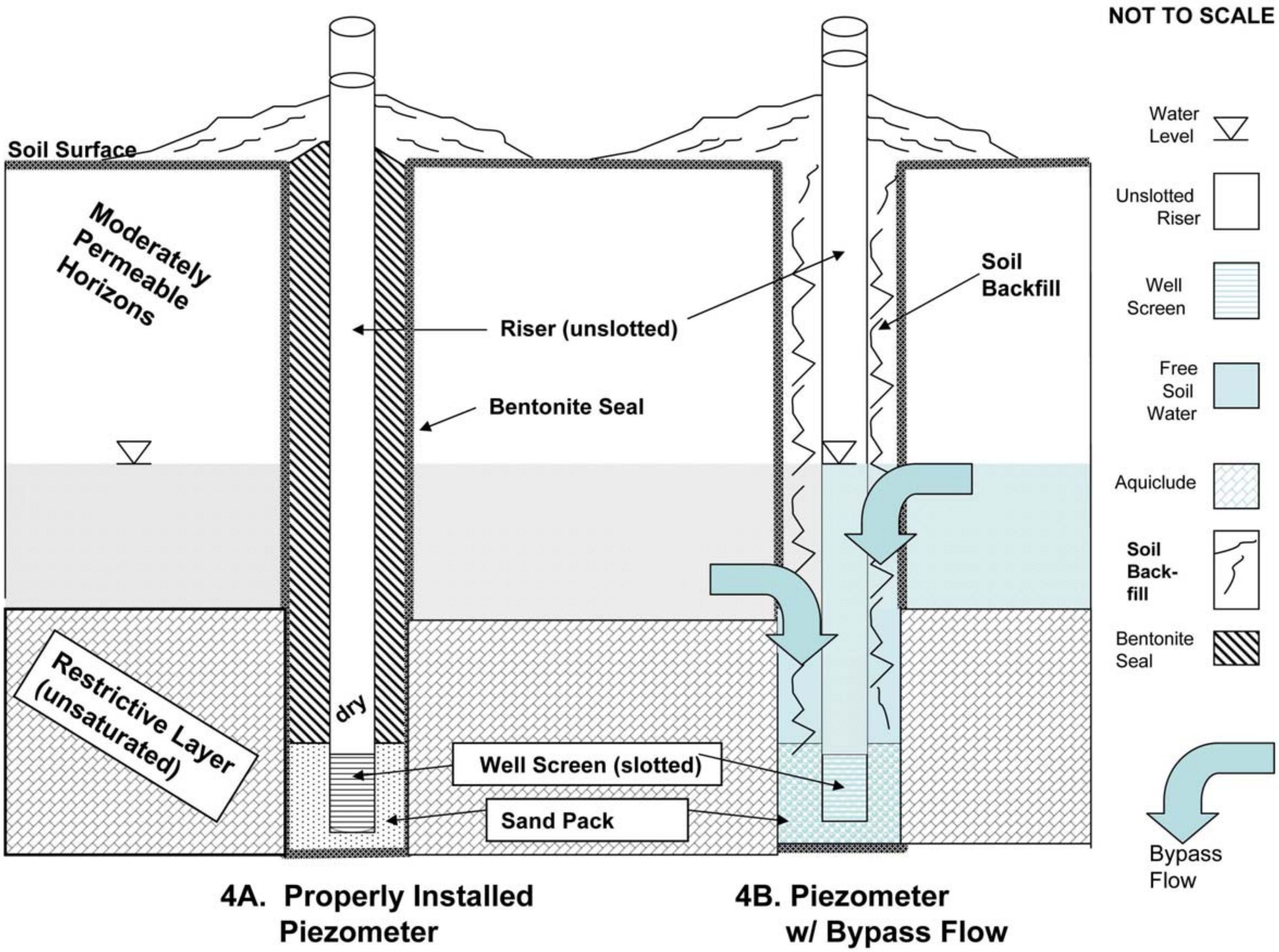
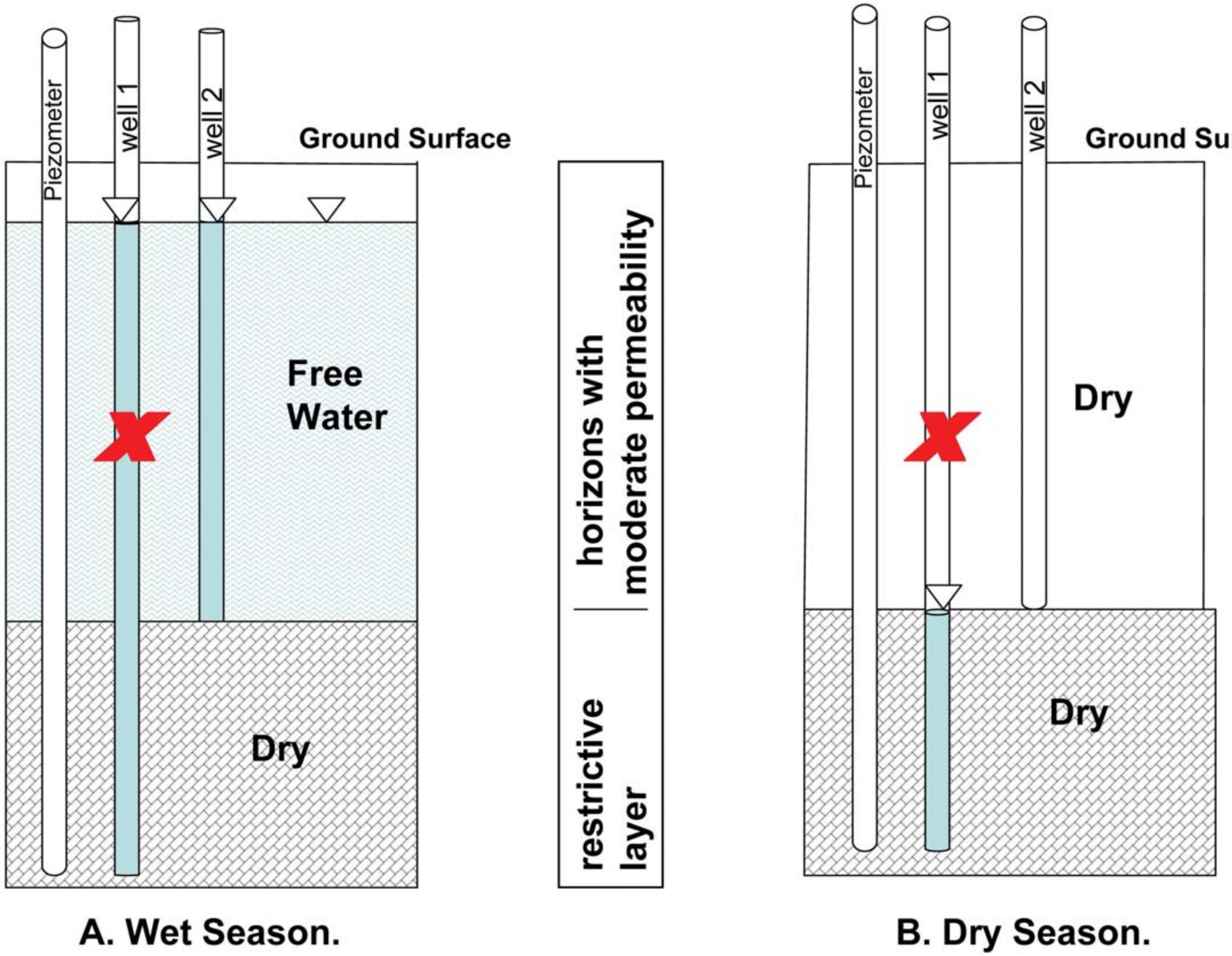


Figure 4. Piezometers **(4A)** properly installed preventing by-pass flow and **(4B)** improperly installed allowing by-pass flow.



A. Wet Season.

B. Dry Season.

Figure 5. Water-table well improperly installed (***X***) to monitor a perched water table. Well 1 acts as reservoir within the restrictive layer. The other two instruments are properly selected to monitor perched water tables. Wells such as Well 1 are frequently reported to retain free water inside low K_{sat} restrictive layers for weeks after the perched water-table has dried out through transpiration.

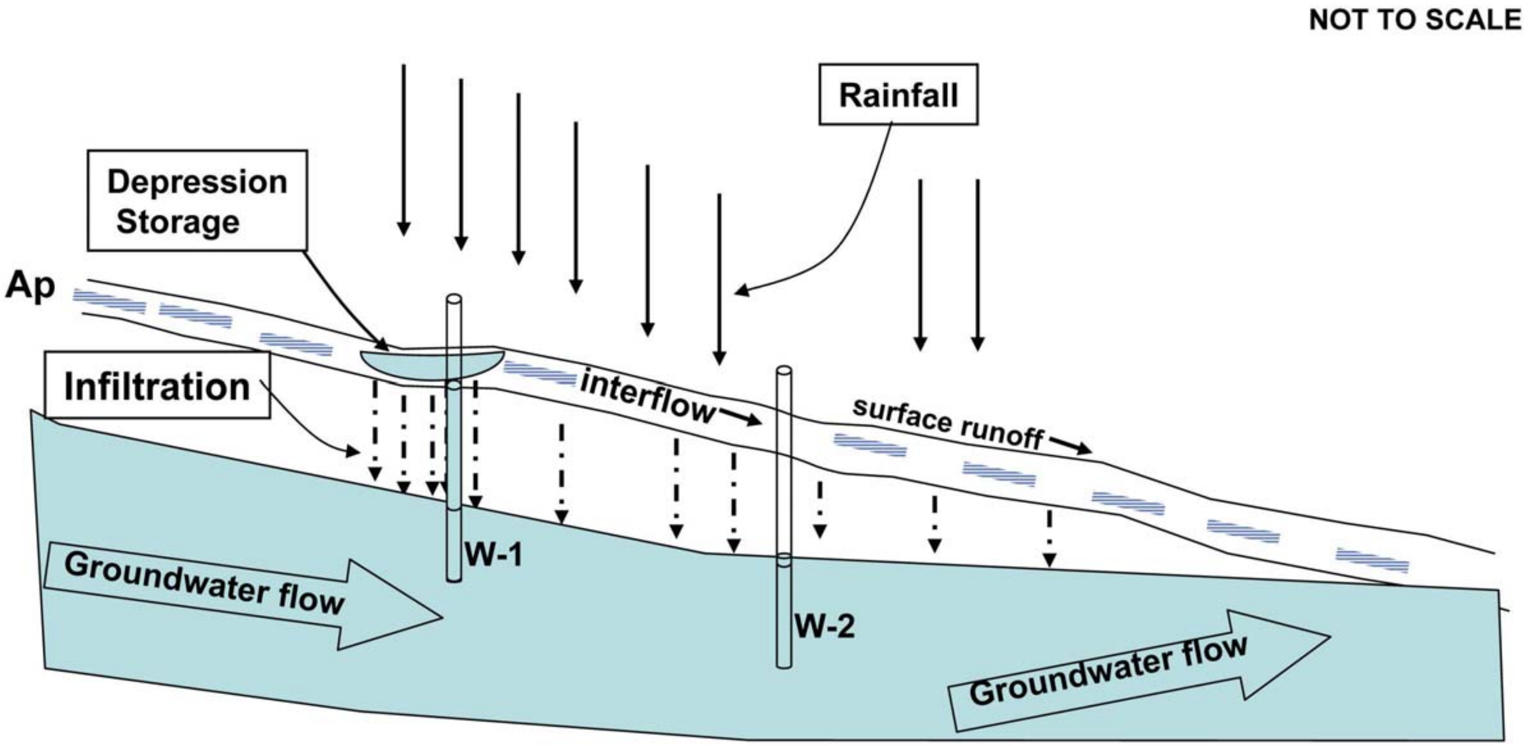


Figure 6. Schematic diagram of paths of water flow significant to shallow water monitoring studies in sloping landscapes. A combination of depression storage and interflow at small scales may be short-lived but can be significant enough to cause bypass flow down poorly protected well risers (W-1). Figure modified from Kirkby (1969).

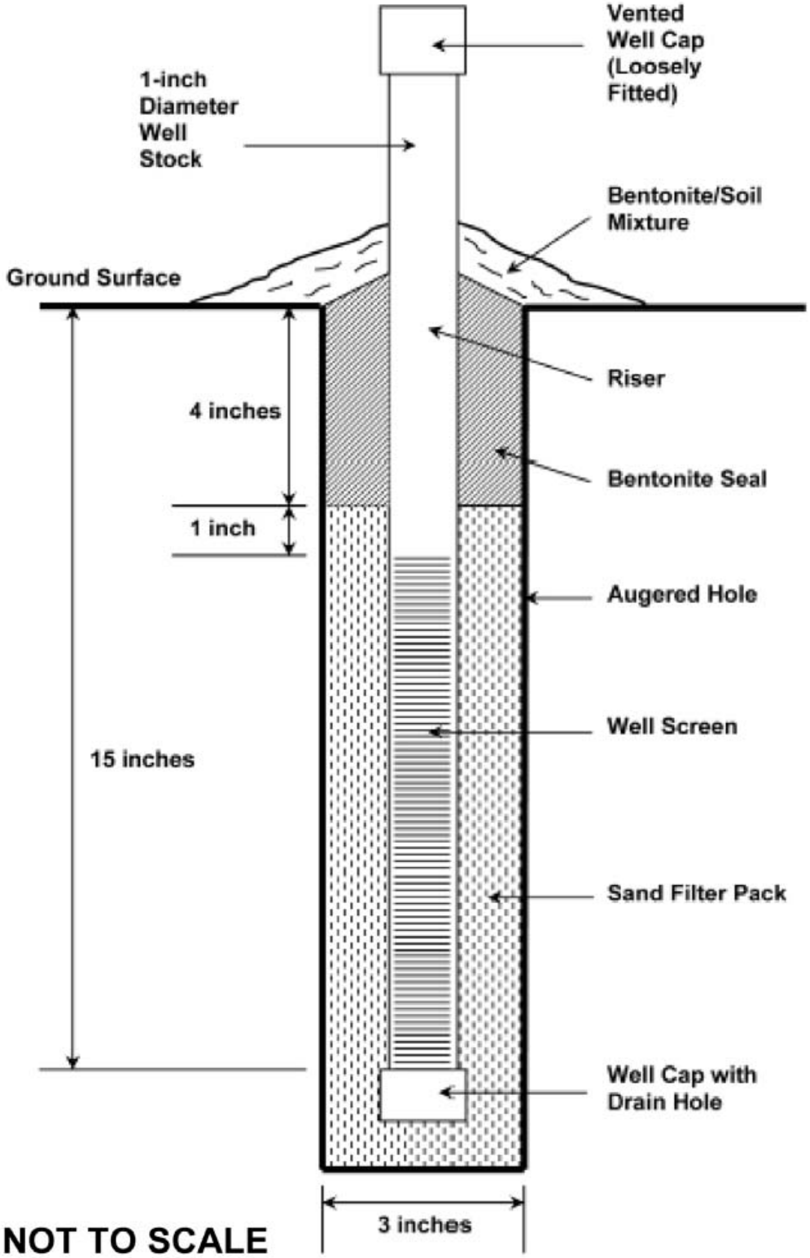


Figure 7. Design of 15-inch deep well recommended for wetland regulatory studies (US Army Corps of Engineers 2005).

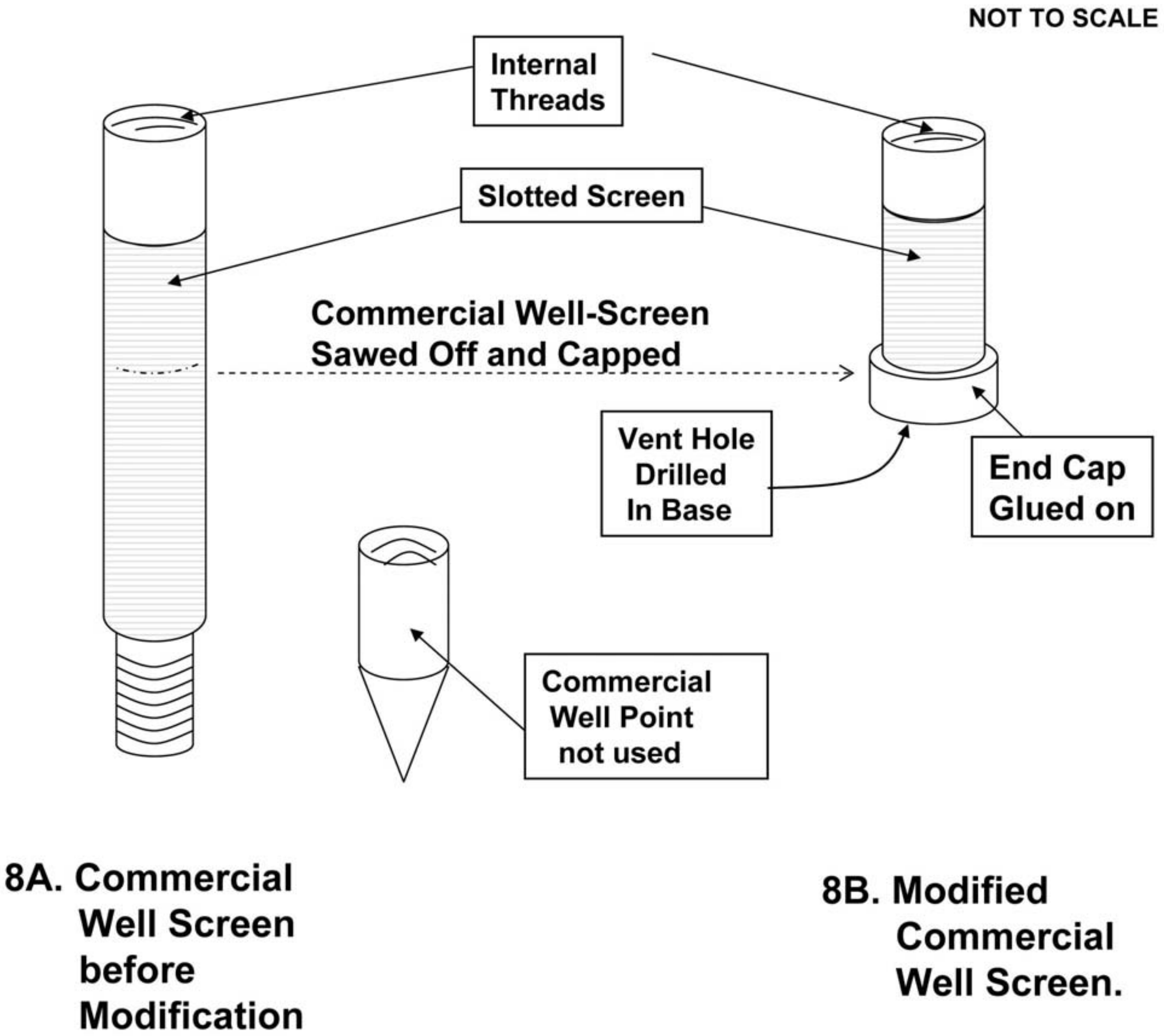


Figure 8. Modified commercial well screen. **(8A)** Commercial well screen with threads at both top and bottom. **(8B)** Screen after sawing off lower threaded portion of pipe and closing with vented PVC plug. Figure modified from Miner and Simon (1997).

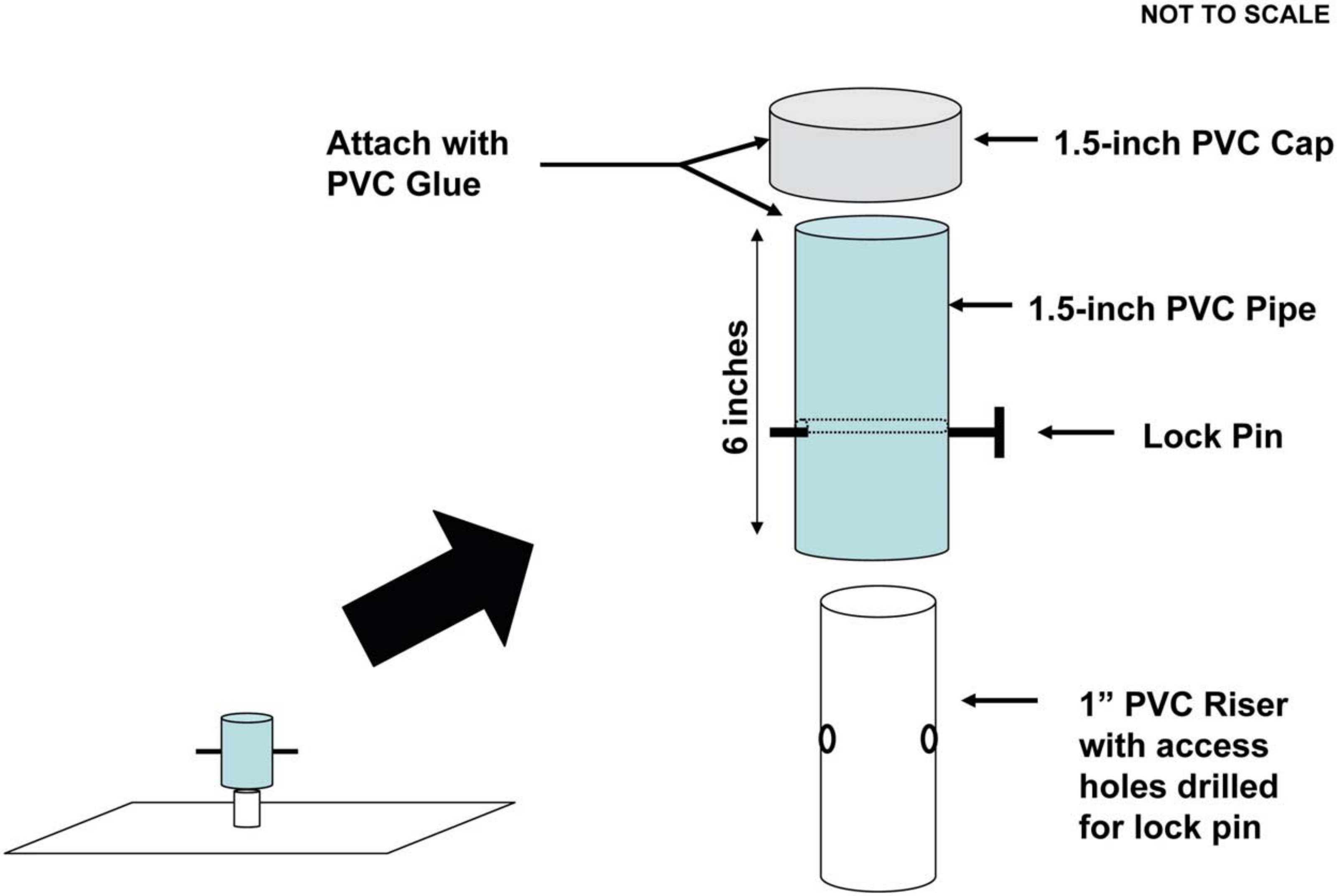


Figure 9. Well-cap made from oversize PVC stock fits loosely over smaller diameter riser and can be attached with a lock pin through drilled vent holes.

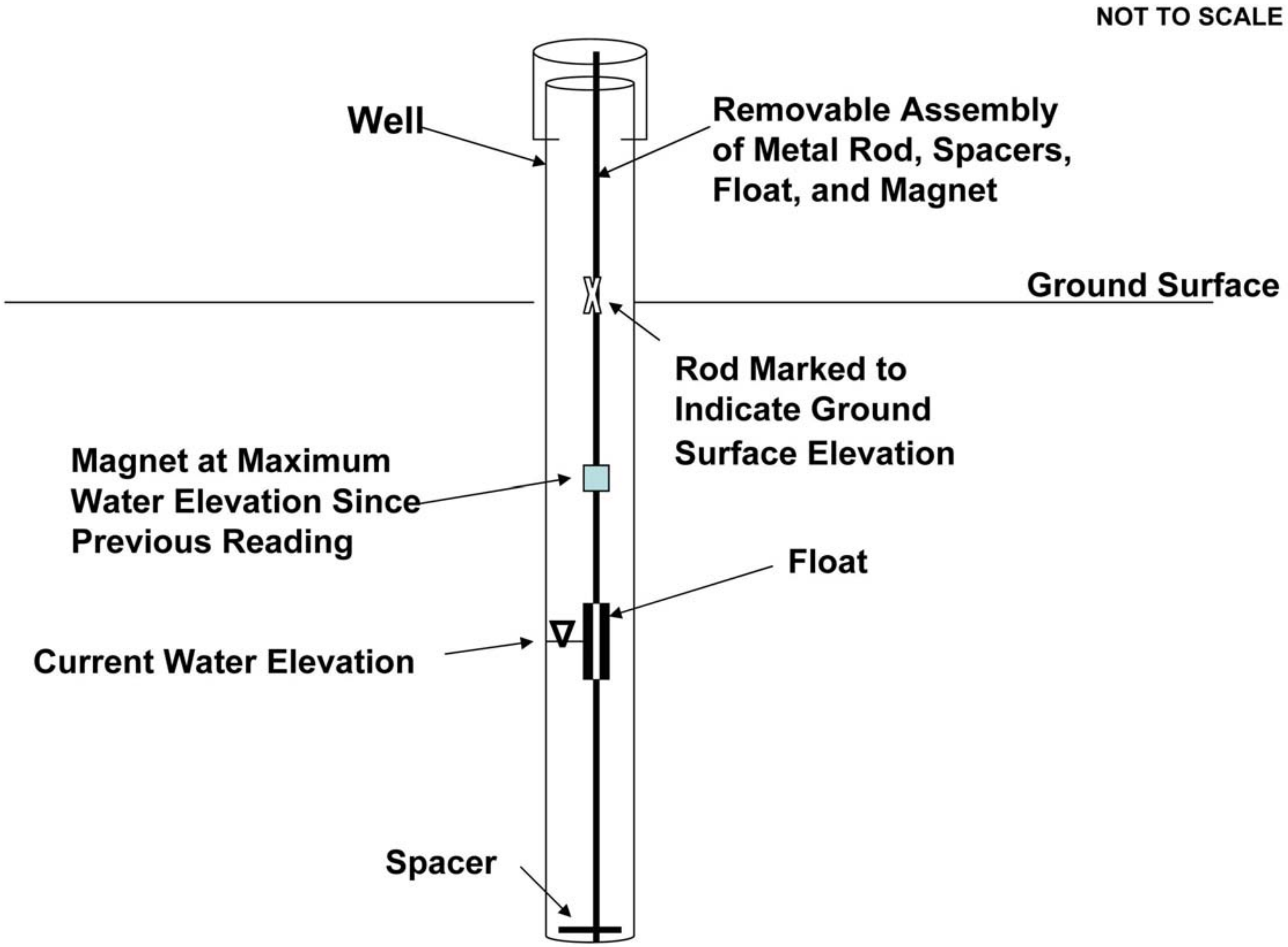


Figure 10. Device for recording maximum water levels between site visits. Rod, float, and magnet assembly is placed inside PVC well. Float moves magnet to maximum water-table level between readings. The entire assembly is removed for measurement, reset, and replaced at each reading. After Morgan and Stolt (2002).

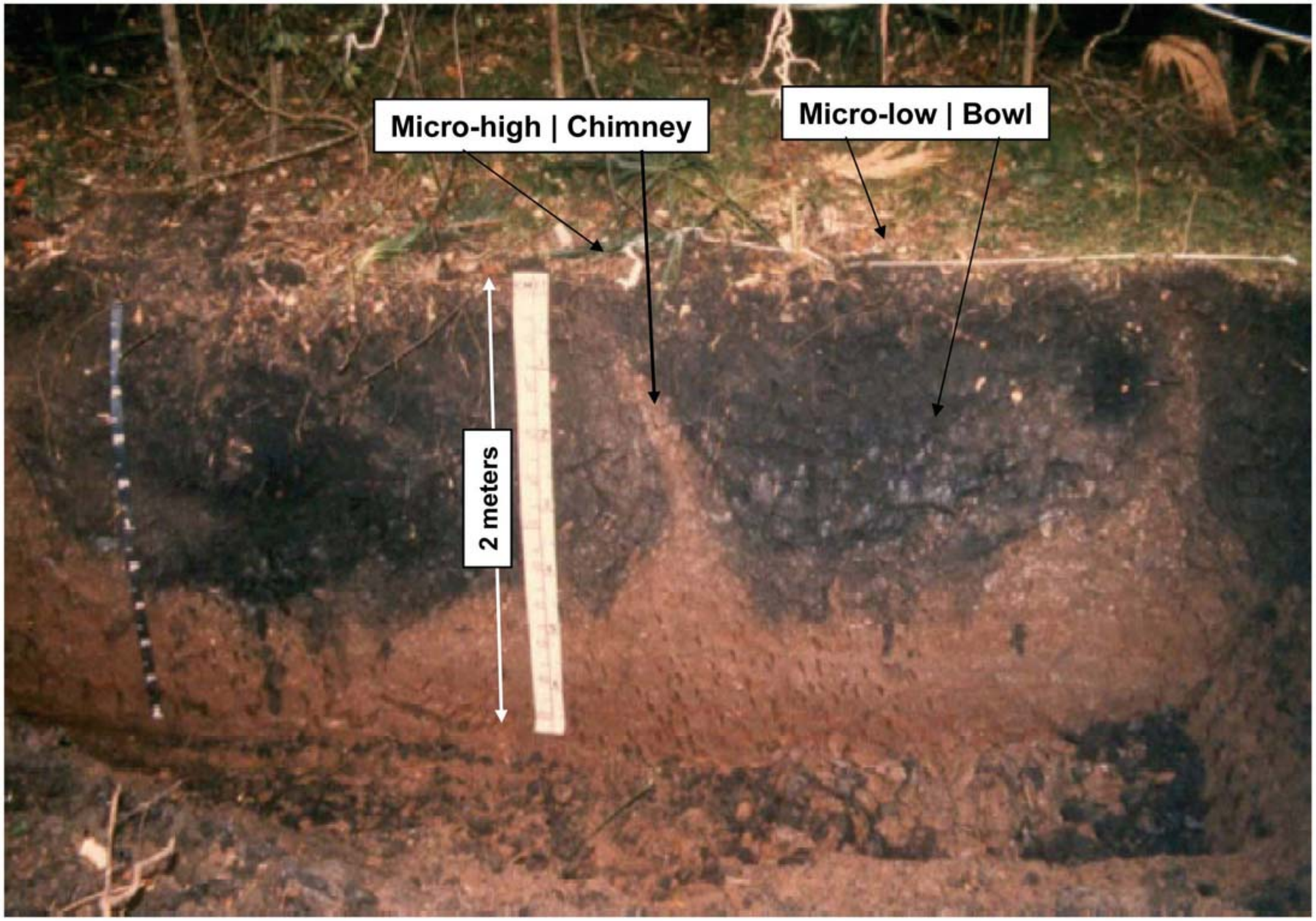


Figure 11. Photograph of chimney-and-bowl morphology of a Vertisol in the Brazoria County, Texas (Miller and Bragg 2007). The white tape is 2 m long. Soil cracks form around the perimeter of the bowl; so rain water flows down chimneys and cause churning over the seasons as the cracks undergo wetting/drying and swelling/shrinking cycles. At least four distinct water regimes may occur in these soils: (1) episaturation in microhighs; (2) episaturation in microlows; (3) progressively less saturation downward, and (4) small pockets of saturation down the chimneys that remain from flow down cracks at the beginning of the wet season. Layers with potential episaturation (1 and 2) should be instrumented with very shallow wells (≤50 cm) and lower layers should be instrumented with replicated piezometers and tensiometers.

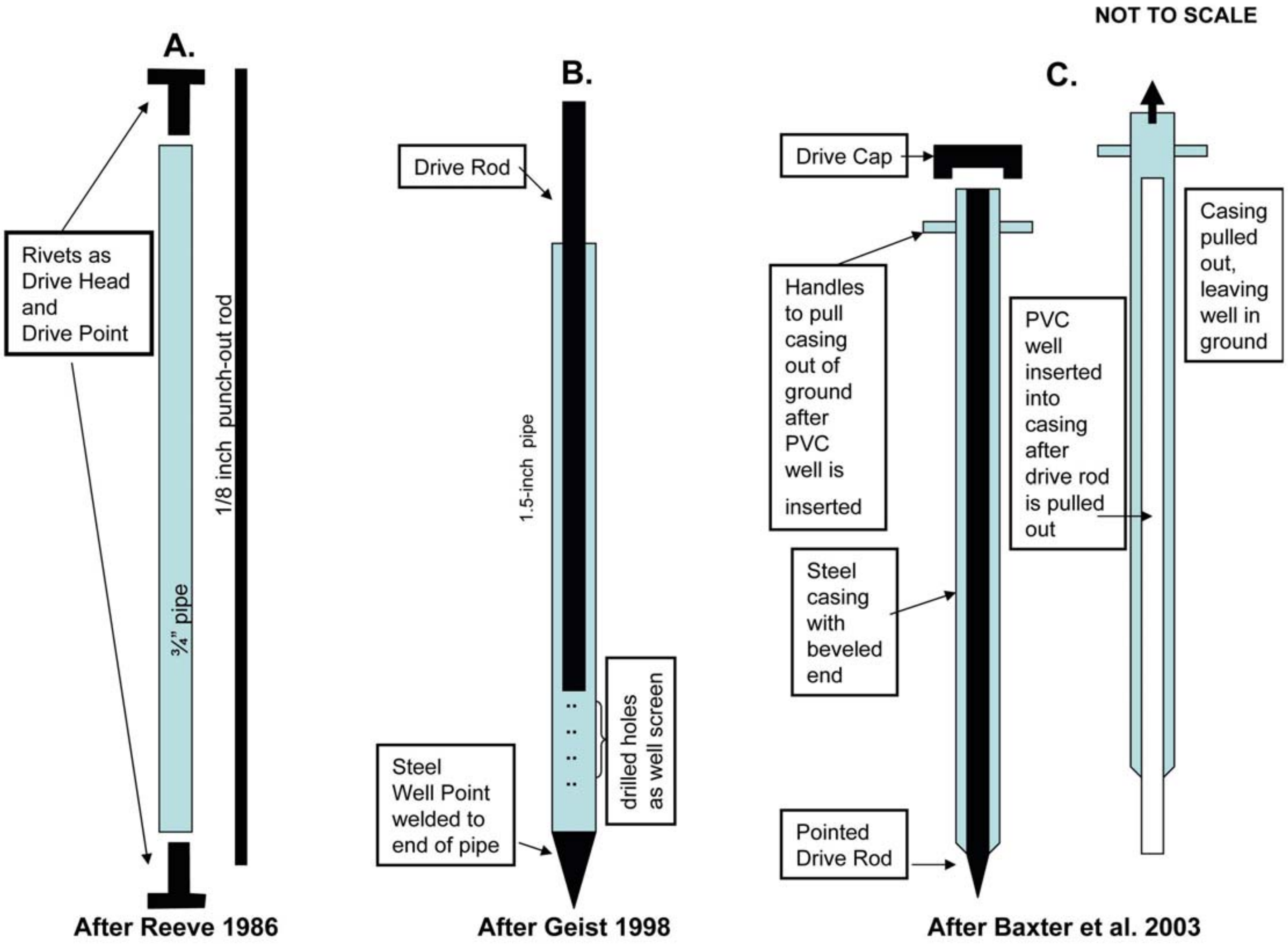
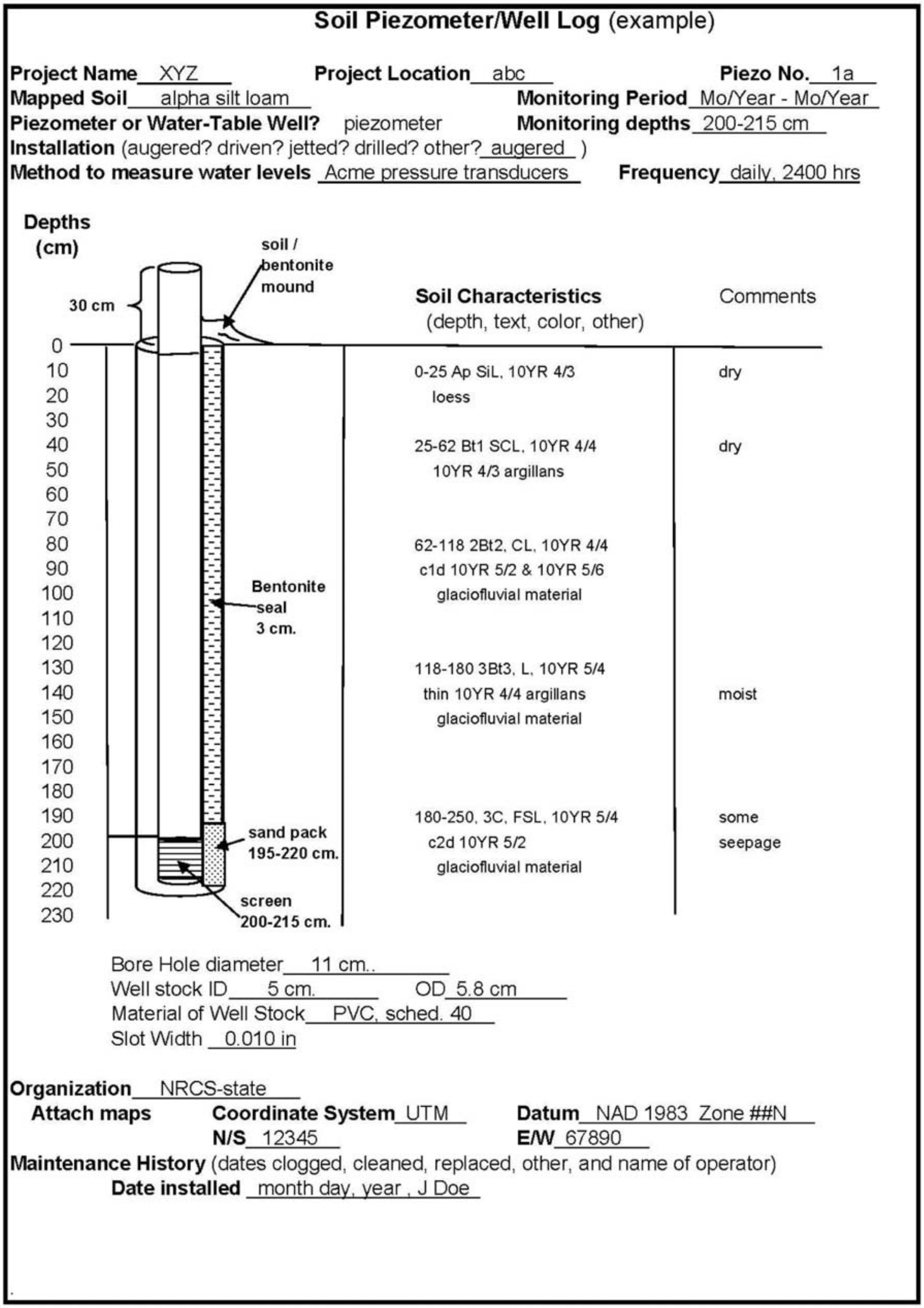


Figure 12. Examples of methods used to install wells when steel stock must be driven through stony material. **(12A)** Drive rod with rivets serving as drive head and well point, with steel well driven down between (Reeve 1988). **(12B)** Steel well with hardened steel well point, driven with drive rod (Geist 1998). **(12C)** Drive rod and machined well case for driving into stony stream beds. After drive rod is removed, PVC well is slipped inside steel drive casing and drive casing is removed for re-use with more wells elsewhere (Baxter et al. 2003).



Soil Piezometer/Well Log (example)

Project Name XYZ **Project Location** abc **Piezo No.** 1a
Mapped Soil alpha silt loam **Monitoring Period** Mo/Year - Mo/Year
Piezometer or Water-Table Well? piezometer **Monitoring depths** 200-215 cm
Installation (augered? driven? jetted? drilled? other? augered)
Method to measure water levels Acme pressure transducers **Frequency** daily, 2400 hrs

Soil Characteristics (depth, text, color, other)	Comments
0-25 Ap SiL, 10YR 4/3 loess	dry
25-62 Bt1 SCL, 10YR 4/4 10YR 4/3 argillans	dry
62-118 2Bt2, CL, 10YR 4/4 c1d 10YR 5/2 & 10YR 5/6 glaciofluvial material	
118-180 3Bt3, L, 10YR 5/4 thin 10YR 4/4 argillans glaciofluvial material	moist
180-250, 3C, FSL, 10YR 5/4 c2d 10YR 5/2 glaciofluvial material	some seepage

Bore Hole diameter 11 cm..
Well stock ID 5 cm. OD 5.8 cm
Material of Well Stock PVC, sched. 40
Slot Width 0.010 in

Organization NRCS-state
Attach maps **Coordinate System** UTM **Datum** NAD 1983 Zone ##N
N/S 12345 **E/W** 67890
Maintenance History (dates clogged, cleaned, replaced, other, and name of operator)
Date installed month day, year , J Doe

Figure 13. Example of data sheet for well installation.

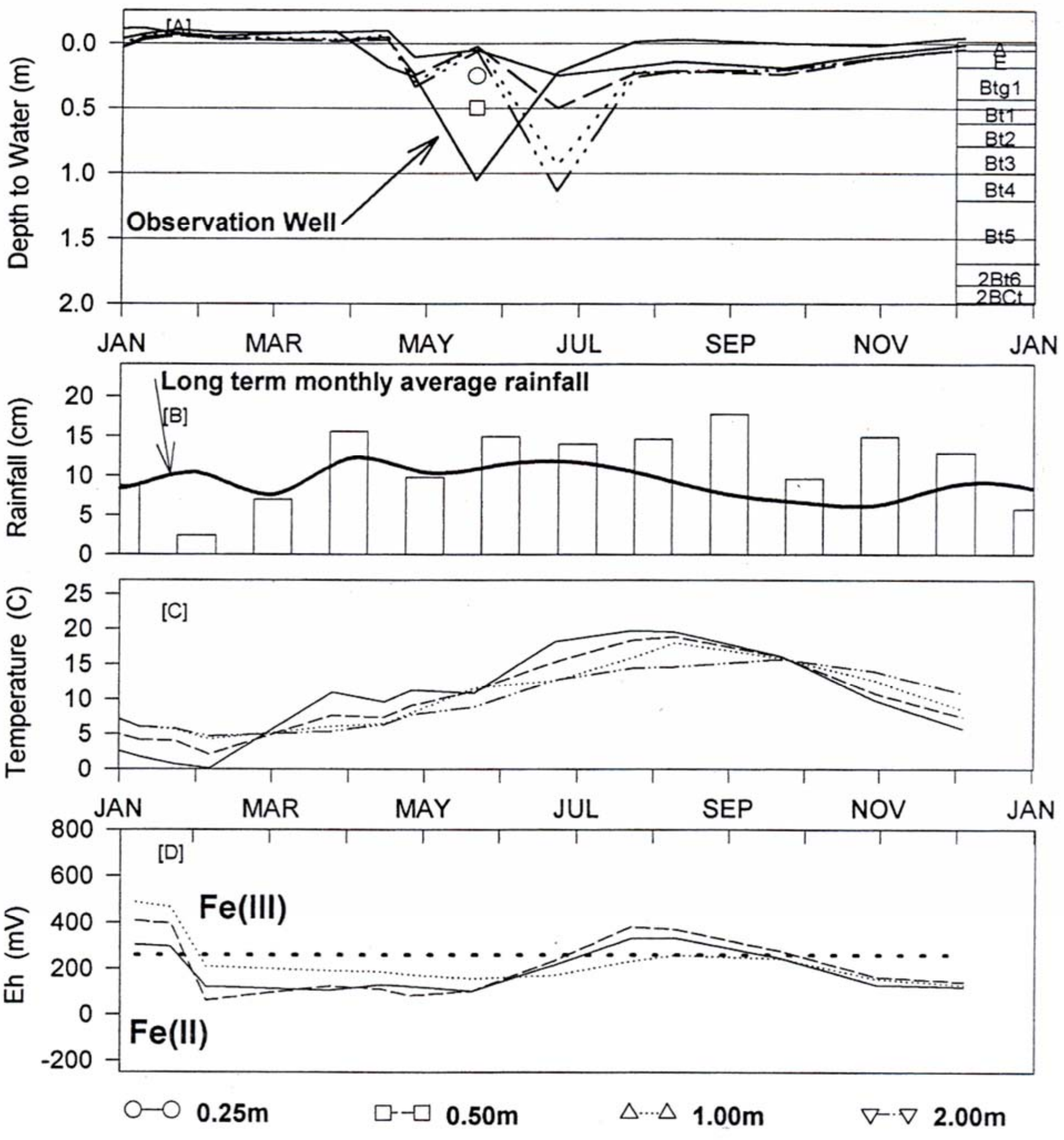


Figure 14. An example of the graphic display of well data with a superimposed soil profile on the right side. Stacked graphs of concurrent meteorological and soil-chemistry data (Jenkinson and Franzmeier 1996).