Underground Tank Technology Update

Vol. 13, No. 1
January/February 1999

Department of Engineering Professional Development   The College of Engineering   University of Wisconsin–Madison

Underground Tank Technology Update is published bimonthly by the University of Wisconsin–Madison, Department of Engineering Professional Development. *UTTU* supplies useful information to federal, state, and local officials working with groundwater technology and to other interested technical specialists. For new subscriptions or address corrections, use the form on inside back page.

UTTU is funded by the U.S. EPA under Cooperative Agreement No. 826455010 to the University of Wisconsin–Madison, which is responsible for its preparation. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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Slug tests

Slug tests enable the hydrologist to determine an aquifer's in-situ hydraulic conductivity. The test is "initiated by causing an instantaneous change in the water level in piezometers through a sudden introduction or removal of a known volume of water. The recovery of water level with time is then observed*" (Freeze and Cherry, 1979)*. "Following this sudden change, the well's water level returns to static conditions as water moves out of the well or into it in response to the gradient imposed by the sudden change in head . . . In certain conditions, the slug test can also be used to obtain an estimate of the formation's ability to release or accept water into storage. This storage capability of the media is characterized in hydrogeology by specific storage" *(Butler, 1998).* See Figures 1 and 2.

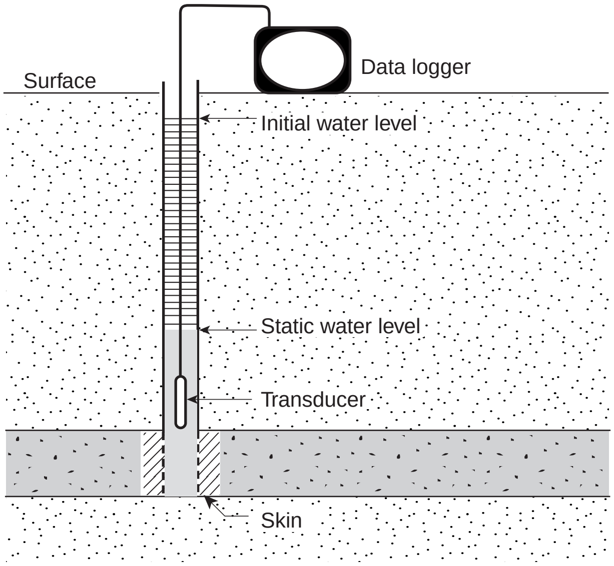

Figure1. Schematic of a slug test setup (from Ramesh, 1991).

Slug, falling-head, slug-in and more

Over the past 40 years, terminology with respect to slug tests has expanded, causing confusion and misunderstanding. For instance, slug tests can be initiated by a sudden rise or a sudden drop in the head in a well, i.e., the direction of the slug-induced flow (into/out of the well) differs. For tests initiated by a sudden rise in head, terms applied include falling-head, slug, slug-in and injection tests. For tests initiated by a sudden drop in head, the terms rising-head, bail-down, bailer, slug-out and withdrawal tests are commonly used. The term "response test" has been used for both situations *(Butler, 1998).*

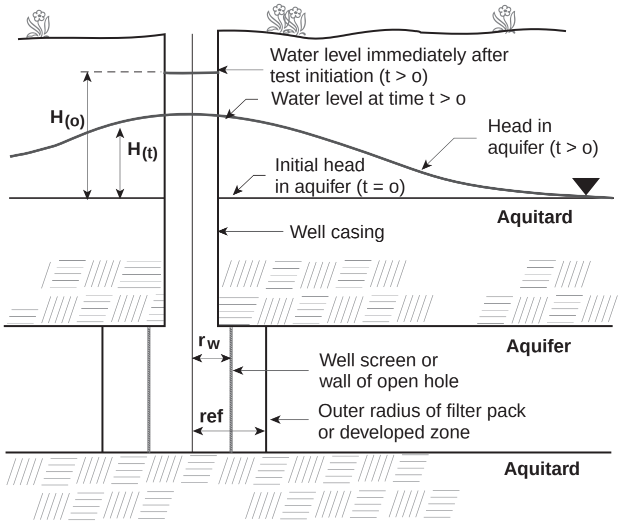

Figure 2. Slug test in a monitoring well that is fully screened across a confined aquifer (from Butler, 1998).

Data analysis

For slug or bail-down tests (response test), hydrologists gather time vs. water level data:

- if a point piezometer is used for the test, the Hvorslev method is used for data analysis
- if the aquifer is confined, the method described by Cooper and others is used
- if the aquifer is confined or unconfined, the Bouwer and Rice method can be used

The Hvorslev method analysis assumes a homogenous, isotropic, infinite medium, and that both soil and water are incompressible. In terms of the test, the rate of inflow, q, at the piezometer at any time, t, is proportional to the hydraulic conductivity, K, of the soil and the unrecovered head difference, H-h, so that:

$$q(t) = \pi r^2\, dh/dt = FK\,(H-h) \qquad (1)$$

where F is a factor that depends on piezometer intake shape and dimensions; H-h is the head difference

Basic lag time, T_o, is described by:

$$T_o = \pi r^2/FKt \qquad (2)$$

Rearranging equation 1 by substituting in equation 2, hydrologists obtain an ordinary differential equation, with the initial conditions, H_o at t = 0:

$$H-h/H-H_o = e^{-t/T_o} \qquad (3)$$

The plot of field recovery data, H-h vs. t, should exponentially decline in recovery rate with time. Recovery rate normalized to $H-H_o$ and plotted on a logarithmic scale produces a straight line plot. Furthermore,

$$T_o = V/q_o \qquad (4)$$

where V is the volume of water added or removed

A plot of the data (H-h/H-H_o vs. t) allows the hydrologist to measure T_o graphically, while K is determined from equation 2. Thus, for a piezometer intake of length L and radius R with L/R > 8 :

$$K = r^2 \ln (L/R)/2LT_o \qquad (5)$$

The Cooper and others analysis considers both formation and water compressibilities. “It utilizes a curve-matching procedure to determine the aquifer coefficients T and S. The hydraulic conductivity can then be determined on the basis of :

$$K = T/b \qquad (6)$$

Like the Theis solution, the method is based on the solution to a boundary-value problem that involves the transient equation of groundwater flow*” (Freeze and Cherry, 1979)*.

The analysis of the bail-test, also involving a plot of recovery data (H-h/ H-H_o vs. t), is prepared with semilogarithmic paper in a reverse format to the Hvorslev test (see Figure 3). When hydrologists use curve matching procedures, values of t and W are read off the horizontal scales, at the matched axis of the field plot and chosen type plot. The matched axes are commonly chosen at W = 1.0. Transmissivity is:

$$T = Wr^2/t$$

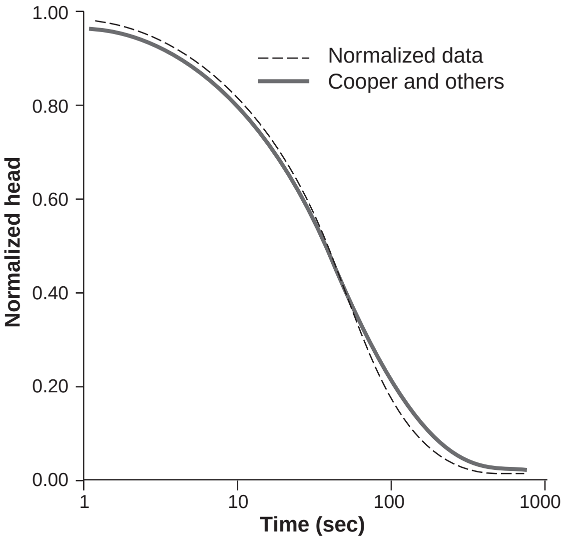

Figure 3. Normalized head (H(t)/H_o) vs. log time plot of a slug test (from Butler, 1998).

The Bouwer and Rice method was originally developed to measure saturated hydraulic conductivity (k) around boreholes for unconfined aquifers, but it can be used for confined or stratified aquifers if the top of the screen or perforated section is some distance between the upper confining layer *(Bouwer, 1989).*

“Anomalies (double straight-line effect) sometimes observed in the measured rate of rise of the water level in the well are attributed to drainage of a gravel pack or developed zone around the well following lowering of the water table. The effect of this drainage can be eliminated by ignoring the early data points and using the second straight line portion in the data plot for calculation of hydraulic conductivity” *(Bouwer, 1989)*.

Hyder and Butler *(1995)* also developed a model that is useful in identifying conditions when conventional approaches introduce large errors into parameter estimates. The model incorporates the effects of partial penetration, anisotropy and an upper constant-head boundary.

Disadvantages of slug (response) tests

Slug or response tests are heavily dependent on high-quality piezometer intake; if the well point or screen is corroded or clogged, measured values may be inaccurate. If the piezometer is developed by surging or backwashing prior to testing, measured values may reflect increased conductivities in the artificially induced gravel pack around the intake *(Freeze and Cherry, 1979)*.

Despite its disadvantages, the slug test is widely used. According to Butler *(1998)*, its advantages include the following:

Low cost: in terms of manpower and equipment, the slug test is considerably less expensive than alternative approaches. A program of slug tests can be performed by one or, at most, two people using a pressure transducer, data logger, and minor amounts of auxiliary equipment. When the cost of the equipment is spread over a large number of tests, the cost per test is extremely low.

Simplicity: the slug test is an extremely simple procedure. One initiates a test by a variety of means and then just measures the changes in head through time. Other than the possibility of having to clean equipment before moving to the next well, little else is required in the field.

Relatively rapid: the duration of a slug test is short in formations considered to be aquifers; in less permeable formations, the test duration can be made relatively short through appropriate test design (e.g., decreasing the effective casing radius).

Useful in tight formations: the slug test may be one of the best options for obtaining in-situ estimates of media properties in formations of low hydraulic conductivity. In these “tight” units, it may not be practical to perform constant-rate pumping tests because of the difficulty of maintaining a very low discharge rate. Although constant-head injection tests are often performed in the geotechnical industry, the logistics of the approach and the need to introduce water into the formation make this technique less attractive for environmental applications. Historically, laboratory testing of core samples has been the method for obtaining information on the properties of low-conductivity media. This technique, however, has become less common recently because core samples may not provide information on a large enough scale to detect existence of preferential flow paths. In addition, it is difficult to obtain an “undisturbed” sample; furthermore, there may be differences between the vertical and horizontal components of hydraulic conductivity.

Water is not required: the technique can be configured so that water is neither removed from or added to the well during the test. This can be done by initiating a test through the addition or removal of a solid slug from the water column, the pressurization-depressurization of the air column in the well.

Provides information on spatial variations in hydraulic properties: a program of slug tests can be designed to acquire information about a formation's transmissive and storage properties at a scale of relevance for contaminant transport investigations. Conventional pumping tests will provide large-scale volumetric averages of hydraulic properties, which may be of limited use in transport investigations. By performing a series of slug tests at discrete vertical intervals within individual wells and/or single tests in relatively closely spaced wells, hydrologists can obtain information on a site's vertical and horizontal variations in hydraulic properties.

Perceived straightforward analysis: the analysis of response data from slug tests is generally straightforward. Most analysis methods involve fitting straight lines or type curves to plots of field data. The boundary effects that may make data analysis from large-scale pumping tests quite involved generally have little to no impact on the response data from slug tests.

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Slug test design

Individuals who design slug tests should consider the following issues *(Butler, 1998),* some of which apply to pumping tests:

- well drilling procedures
- well development activities
- well skin effect
- screen length and size of screen openings
- filter pack radius
- nominal radius of well with respect to well efficiency
- number of slug tests performed at each well
- direction of groundwater flow

Well drilling procedures that minimize the generation of drilling debris should be used whenever possible. Driving-based methods such as cable-tool, pneumatic/hydraulic hammering, or rotosonic methods are probably best. The approach used will depend on hydrogeologic conditions and purpose of the well.

Well development activities should focus on developing discrete intervals along the well screen. Well development refers to the post-drilling procedures such as simple pumping, surging, introduction of various fluids, or use of downhole explosive devices. These activities remove drilling debris or other human-induced biochemical action from the near-well portions of the formation adjacent to the screened (open) interval. Well development "is the single most important aspect of a program of slug tests," but it is "all too often a neglected component of field investigation. The result is that the parameter estimates obtained from slug tests may have a rather tenuous connection to reality" *(Butler, 1998)*.

Development procedures that do not stress discrete portions of the well screen may prove ineffective, leaving substantial portions of the screened interval virtually untouched by development. Vertical flow within the filter pack can diminish the effectiveness of development efforts, thus consideration should be given to use of post-installation procedures that may result in more complete development. These include development prior to emplacement of the filter pack in stable formations, use of specially constructed filter packs that decrease vertical flow, or use of natural filter packs in unstable formations.

The well skin refers to the altered near-well zone, which can be biochemical or physical in nature. The skin can have a hydraulic conductivity that may be lower (low-K skin) or higher (high-K skin) than the formation itself. Low-K skin possibilities should be assessed by a preliminary analysis of the response data using a theoretical model for slug tests in homogeneous formations. Low-K skins will have a more dramatic impact on slug-test response data than high-K skins. It may be impossible to remove the effects of a low-K skin. A physically implausible specific storage estimate strongly suggests that a skin is affecting the response data.

The nominal screen length should be used for the effective screen length parameter in practically all cases. Screen length is related to efficiency of well development: the longer the screen, the greater the potential to have significant portions of the tested interval remain untouched by well development. The size of the screen openings (slots) depends on the formation's characteristics. Slot size is critical in wells without an artificial filter pack because inappropriate sizing can greatly complicate well development efforts and therefore potentially introduce errors into the hydraulic conductivity estimate obtained from a slug test. In screens with a relatively small percent of open surface area, such as might be found when the slots have been made by hand or a downhole casing perforator, convergent flow to the sparsely distributed slots may produce additional head losses that can complicate test data analysis.

The filter or gravel pack is the material that is placed in the annular space between the inner diameter of the borehole and the outer diameter of the well screen. The pack usually forms a zone of higher hydraulic conductivity immediately outside the screen. If the material is added from the surface, the filter pack is "artificial"; if the material consists of formation material that collapses against the screen when the support provided by the drill pipe or temporary casing is removed, the filter pack is natural. The purpose of the filter pack is to stabilize the formation by decreasing the potential for movement of fine material into the well; in stable formations, it provides support for the overlying annular seal. The radius of the filter pack should be used for the effective screen radius parameter in wells with artificial filter packs, while the nominal screen radius may be a better choice for wells with natural filter packs if development has been limited.

The nominal radius of the well casing should be used for the effective casing radius in conventional slug tests. If there is entrapped air in the filter pack, or the filter pack extends across the water table, this may not be appropriate. A comparison of the theoretical and measured values for the initial displacement will indicate the appropriate radius for a particular test. The effective casing radius will be a function of the compressibility of water and test equipment used in the case of a shut-in slug test. The casing radius controls test duration and the type of equipment that can be used. In small-diameter wells sited in media of very high hydraulic conductivity, the velocity in the casing may be great enough to produce additional head losses, complicating response data analysis.

Three or more slug tests should be performed at each well. Two or more different values for the initial displacement (varying by at least a factor of two) should be used in these tests. The first and last tests of the series should use the same H_o (initial head displacement) so that the effects of a dynamic skin can be separated from a reproducible dependence on the initial displacement. The direction of flow should also be varied between tests so that a skin-related directional dependence can be identified and, for the case of a well screened across or near the water table, the appropriate manner to represent the water table can be determined. These results of repeat tests should identify effectiveness of well development activities and the viability of conventional slug-test theory to be evaluated at each well.

The primary direction of flow during a series of slug tests should be from the formation into the well. Slug-induced flow from the well into the formation will often lead to decreases in hydraulic conductivity as a result of mobilized fine material being lodged deeper in the formation.

Reference

Butler, J.J. Jr., *The Design, Performance, and Analysis of Slug Tests,* 1998, Lewis Publishers, CRC Press LLC, 2000 Corporate Blvd. N.W., Boca Raton, Florida 33431; 800-272-7737.

Pumping tests

Hydrologists use pumping tests to determine a formation's transmissivity, T, and storativity, S. Unlike piezometer or laboratory tests, pumping tests give "in-situ measurements that are averaged over a large aquifer volume" *(Kruseman and de Ridder, 1979).*

The hydraulic conductivity value will be used for natural attenuation or RBCA (risk-based corrective action) determinations. It may be more appropriate to use the highest measured value as described in "Four Critical Considerations in Assessing Contaminated Groundwater Plumes," *UTTU*, Vol. 12, No. 2, 1998. *Editor's note: The guidance described above promotes the use of the geometric mean to average a number of hydraulic conductivity results to obtain a single value for design of a groundwater extraction system.*

Preliminary work for pumping tests

Prior to performing an aquifer test, the hydrologist should obtain the following geological and hydrological information:

- geological features of the aquifer, such as lithology and thickness
- character and thickness of the overlying and underlying beds
- groundwater flow direction, water table gradients, regional water-level trend

This information helps site investigators decide what equipment is needed and the number and location of well tests.

Estimating transmissivity

During well drilling, samples of the sediment and rock should be obtained and described accurately, giving special consideration to the grain size. "On this basis, the length of the pump screen and depth at which the screen should be installed can be decided" (*Kruseman and de Ridder, p. 25, 1979)*. Samples should be sent to a laboratory because

- geological analysis may give information on the stratigraphic position of the layers
- a more detailed lithologic description of the samples can be made to obtain grain size, grain sorting and clay content, all which affect the hydraulic conductivity

With this data, hydrologists can obtain an "initial impression" of the hydraulic conductivity and transmissivity. "A relationship can be established between the hydraulic conductivity and the grain size. The effects of sorting, amount of clay and gravel may also be estimated. If tables or graphs of these relationships are not available, the hydrologist may divide the aquifer materials described in the logs into major groups, ranging from very fine sand to gravel, and assign by estimation a certain hydraulic conductivity coefficient to each group. For each layer described in the well log, this coefficient is multiplied by the thickness of the layer to find the transmissivity of the layer. By summing these results, the transmissivity of the aquifer at the well site may be estimated. This geologic approach to determining transmissivity is repeated for each well used in the actual aquifer test and the results are averaged. The estimated transmissivity value thus obtained can be compared with the result obtained from the actual test. If no agreement is found, the error percentage should be determined. When this percentage is known for each test site, a correction can be made on transmissivity values estimated from the logs of wells located between these test sites."

"Experience has shown that if accurate well logs are available, the transmissivity can be estimated with reasonable accuracy. However, appreciable errors may be made when either very fine materials (clay and silt) or very coarse (gravel) are mixed with the sand" *(Kruseman and de Ridder, p. 24-25, 1979.)*

Pump or discharge well

A pump or a discharge well has a tube that is screened in the aquifer. A pump in the well lifts the water to the surface. Characteristics of the well are as follows:

- well diameter should be large enough to accommodate the pump and assure hydraulic efficiency
- well depth is usually determined from the log of a test hole, but it should be completed to the aquifer bottom
- well screen length
  - doubling the diameter will increase the yield only by about 10 percent
  - in non-homogeneous aquifers with intercalated clay beds, separate tests may be made in different aquifer parts
  - a proper screen, which allows a water flow of less than 3 cm/sec, should be used to minimize friction losses
  - size of screen openings should be based on aquifer grain size material
- gravel pack should be artificially graded coarser material (coarser than the formation) that facilitates entrance of formation water into the well
  - ideally, the gravel pack should retain all of the formation material where water enters into the well
  - pack should consist of clean, rounded, uniformly smooth grains
  - pack thickness should be 7–8 cm to ensure that an envelope of gravel will surround the entire screen

Kruseman and de Ridder *(1979)* indicate that "after the pump is installed, the well should be developed by pumping at a low discharge rate. When the pumped water becomes clear, the discharge rate is increased and pumping is continued until the water clears again. This procedure is repeated until the desired discharge rate for the actual test is reached or exceeded." The development of the discharge well can serve as a check on the observation wells. During development and testing, discharge water should be prevented from re-entering the aquifer.

Piezometers

When the discharge well is pumped, the water table is lowered, and this lowering is measured in nearby piezometers. The number of piezometers will depend not only on the funds available but on the level of accuracy required. Kruseman and de Ridder *(1979)* maintain that "data obtained by measuring the drawdown in a single piezometer often permit calculation of the average hydraulic conductivity and transmissivity of the aquifer and storage coefficient." With water measurements from at least two piezometers, hydrologists can analyze time-drawdown and distance-drawdown data. Piezometer placement will also depend on aquifer type.

In confined aquifers, hydraulic head loss propagates quickly because the release of water from storage is entirely due to aquifer material and water compressibility. Loss of head may still be measurable as far as a few hundred meters from the well (see Figure 4).

In unconfined or water-table aquifers, propagation of hydraulic head losses is slow because water release from storage is predominantly due to dewatering of the zone through which the water is moving, and only partly due to water and aquifer compressibility. Unless the period of pumping is extended for several days, the loss of hydraulic head caused by pumping is measurable only within about 100 m of the pumped well.

Semi-confined aquifers are intermediate, and loss of hydraulic head will depend on the hydraulic resistance of the semi-pervious layer and whether the aquifer more closely resembles a confined or unconfined aquifer.

Another issue of concern is well-screen length. "The choice of distances from the pumped well at which piezometers should be installed may be strongly influenced by the length of the well screen in the pumped well. If the discharging well is a fully penetrating one, i.e., a well whose screen penetrates the entire thickness of the aquifer, or at least 80 percent of it, the flow of water to the pumped well will be horizontal. Therefore, drawdowns measured in piezometers placed even at short distances from the pumped well can be used for the analysis" *(Kruseman and de Ridder, 1979)*.

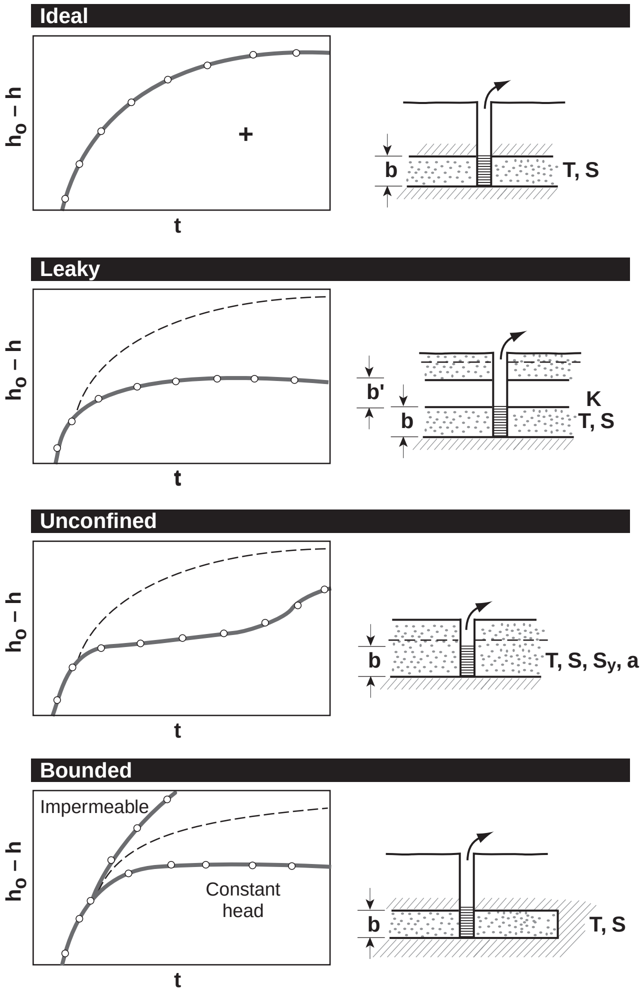

Figure 4. Comparison of log–log $h_o - h$ *vs.* **t** *data for ideal, leaky, unconfined, and bounded systems (from Freeze and Cherry, 1979).*

"In many cases conditions may not allow a well screen to be installed over the entire aquifer thickness. In such a partially penetrating well, the relatively short length of the well screen will cause a non-uniform distribution of head or drawdown that is most noticeable near the well. So if the length of the well screen is considerably less than the saturated thickness of the aquifer, a distorted drawdown pattern is induced near the well, due to vertical flow components. Drawdown readings from wells close to such a partially penetrating well may give incorrect data, and rather complicated correction methods have to be applied before those readings can be used for test data analysis. These difficulties can be avoided if piezometers are placed farther away from the pumped well where these abnormal effects do not appear. As a general recommendation, the nearest piezometers should be placed at a distance that is at least equal to the thickness of the aquifer. At such a distance, flow is assumed to be horizontal" *(Kruseman and de Ridder, 1979).*

Kruseman and de Ridder suggest that piezometers be placed 10 to 100 m from the pumped well, although distances must be greater from thick or stratified confined aquifers, maybe 100 to 250 m. Having a piezometer beyond the radius of influence of the pumped well gives information on the unaffected water table level. Piezometers should be installed at about the same depth as the middle of the well screen in the pumped well, in uniform and homogeneous aquifers. It may be wise to install piezometer screens above and below any clay beds. Generally, the piezometers should be small in diameter to record water levels rapidly and accurately. Kruseman and de Ridder give more details on piezometer construction.

The actual pumping test

According to Freeze and Cherry *(1979)* and Kruseman and de Ridder *(1979),* the actual test involves

- drilling the test well
- installing one or more observational piezometers
- use of a short-term pumping test that involves pumping water during a certain time and at a certain rate from a well having a screen in the aquifer; the effect of this pumping on the water table is measured in the pumped well and nearby piezometers; drawdowns are measured in these piezometers, and their distance from the pumped well, and the well discharge data are inserted into an appropriate formula
- use of the formulas using T and S (described later in this article) to design production well(s) that won't lead to excessive long-term drawdowns

"Most pumping test formulas are based on the assumption that the tested aquifer is of infinite lateral extent. Although such aquifers do not exist, many aquifers are of such wide extent that for all practical purposes they can be considered infinite. Others, however, are of limited extent because they terminate against impervious material. Such barrier boundaries are, for example, the impervious bedrock sides of a buried valley, a fault or simply lateral changes in lithology of the aquifer material. Of equal importance are the recharge boundaries along which there is no drawdown. A recharge boundary exists where an aquifer is freely connected hydraulically with a perennial river, a canal, a lake or the ocean" *(Kruseman and de Ridder, 1979)*.

Analysis of the time-drawdown data relies on curve matching. The two methods used are the Theis method and the Jacob methods; Theis involves curve matching on a log-log plot, whereas Jacob uses a semilog plot. Again, this discussion is taken from Freeze and Cherry *(1979)* and the reader requiring more detail should obtain this book. Steps for determining S and T from a pumping test are as follows:

- plot the function $W(\mu)$ vs. $1/\mu$ on log-log paper (this plot of dimensionless theoretical response is known as a type curve; see Figure 5)
- plot the measured time-drawdown values, h_o–h vs. t, on log-log paper of the same size and scale as the $W(\mu)$ vs. $1/\mu$ curve

- superimpose the field curve on the type curve, keeping the coordinate axis parallel; adjust the curves until most of the observed data points fall on the type curve (see Figure 6)
- select an arbitrary match point and read off the paired values of $W(\mu)$, $1/\mu$, h_o-h and t and match point; calculate μ from $1/\mu$
- using these values together with the pumping rate Q and the radial distance r from well to piezometer, calculate T using

  $T = QW(\mu)/4p(h_o\text{-}h)$

  (See also "Darcy's law" in definitions on page 11.)
- calculate S using $S = 4\mu Tt/r^2$

Alternative equations for T and S are

$T = AQW(\mu)/h_o\text{-}h$

$S = uTt/Br^2$

A and B are coefficients used to ensure consistency of units. They vary depending on the units used in calculations.

The process of curve matching can also be used to determine T and S for leaky and unconfined aquifers, although these aquifers will use a curve different from those used by confined aquifers (see Figure 7). If the purpose of the test is to determine long-term aquifer needs, then the design of the pumping test configuration should contain observational piezometers in the aquitards as well as in the aquifer *(Freeze and Cherry, 1979)*.

Sometimes the analytical methods (presented above) are not sophisticated enough to handle heterogeneous aquifers of irregular shape; for these aquifers, hydrologists use numerical simulations involving either a finite-difference formulation or a finite-element formulation. For more detail, see Freeze and Cherry *(1979)*.

Pumping tests have these advantages:

- they provide in-situ parameter values, which are averaged over a large and representative aquifer volume
- the tests give information on conductivity and storage properties
- in aquifer-aquitard systems, they provide information on leakage properties

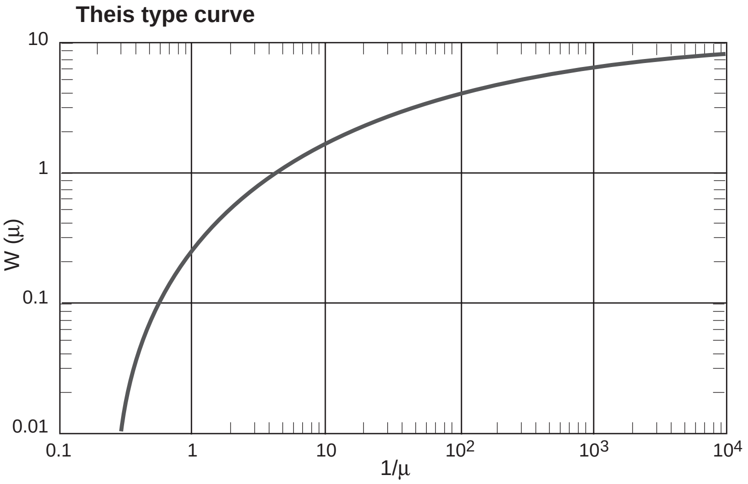

Figure 5. Plot of W(μ vs. 1/μ(Heath, U.S.G.S., 1983).

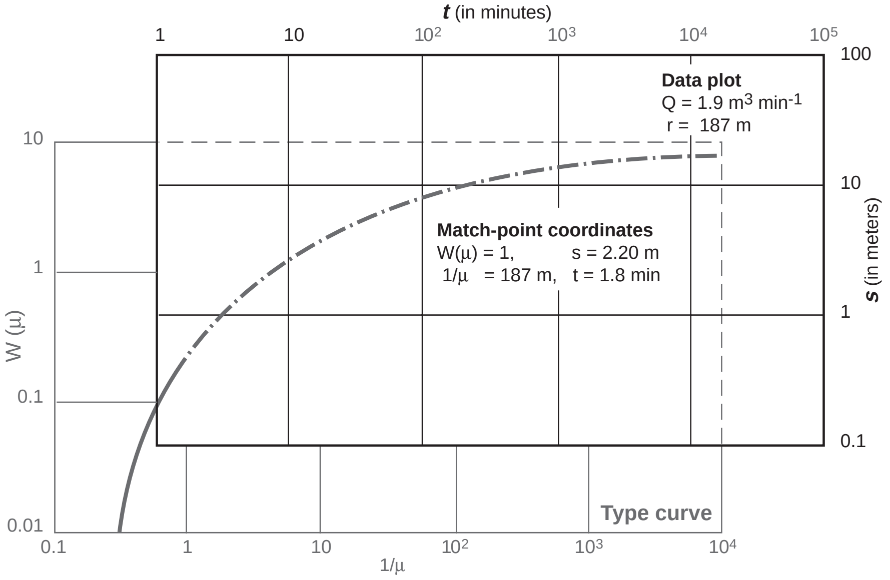

Figure 6. Superimposing field curve on type curve (Heath, U.S.G.S., 1983).

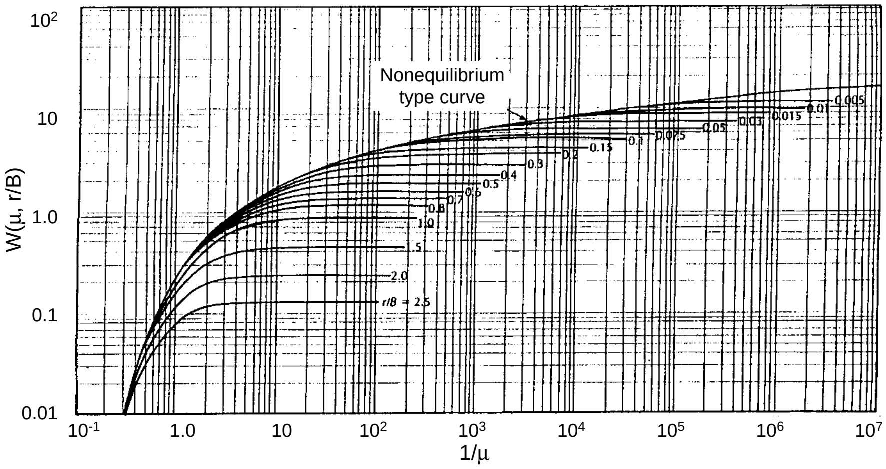

Figure 7. Type curves of leaky artesian aquifer original source: W.C. Walton, Illinois State Water Survey Bulletin 49, 1962 (from Fetter, 1994).

Disadvantages include

- nonuniqueness of the pumping test interpretation: a similarity of time-drawdown responses can arise from leaky, unconfined and bounded systems, and unless geologic evidence clearly supports one system, then the studied aquifer may not fit the assumption on which the curve is based
- expense: pumping tests require more time and wells than slug or bail-down tests

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Aquifer testing

The following article is abstracted from the Wisconsin document *Guidance for Design, Installation and Operation of Groundwater Extraction and Product Recovery Systems*.

Hydrologists test aquifers to estimate the hydraulic conductivity or transmissivity for plume capture calculations. Hydraulic conductivity tests, which include pumping tests, slug tests, bail-down tests and grain-size methods, can

- provide sufficient data for remedial design
- estimate groundwater pumping rate needed to capture plumes
- provide sufficiently accurate hydraulic conductivity estimates

The following is a list of aquifer tests in decreasing order of accuracy of data obtained:

- long duration (multi-day) constant-rate pumping tests
- short duration (less than eight hours) step-drawdown tests
- bail-down and slug tests
- permeability calculations based on grain-size analysis

Wisconsin provides guidelines regarding use of these tests:

- a plume in sand or gravel that is hundreds of feet long and more than 100 feet wide is a major groundwater extraction project; therefore, a pumping test is probably necessary
- in silt and clay soils, a pumping rate is generally several gpm or less; a bail-down test from each well usually provides sufficient data for evaluating design, treatment and/or disposal options, although a pumping test more clearly defines an aquifer; it may be more cost effective to oversize the groundwater extraction/treatment system and delay a pumping test until after system installation, provided that oversizing the groundwater treatment system is relatively inexpensive
- a pumping test is probably needed prior to designing groundwater extraction systems that are likely to produce more than 50 gpm, but it is probably not necessary for systems that are likely to operate at less than 5 gpm; if the system is projected to produce between 5 and 50 gpm, designers should assess site-specific factors such as water disposal options and treatment needs to determine accuracy level required

In addition, a careful evaluation of pumping test costs and benefits may be warranted. If a pumping test is not proposed at a site, the hydrogeologist should include the appropriate data to justify the exclusion.

If a number of aquifer results are available, the geometric mean of the results should be used to calculate the average hydraulic conductivity. If multiple hydrogeologic units are present, designers should calculate the geometric mean for each hydrogeologic unit, not a single, overall site average. If some results have a higher degree of certainty, designers should not use the results that are less certain in the calculations. For example, if both pumping test results and Hazen method results are available, the Hazen method results should not be used when calculating the geometric mean due to the higher level of uncertainty.

Groundwater discharged during an aquifer test or well development should be sampled and chemically analyzed for contaminants and other parameters that may affect the treatment system and/or disposal options.

Water produced as part of aquifer testing must be handled in accordance with DNR (Department of Natural Resources) rules applicable to investigating wastes. Potable, low-volume air strippers or carbon filters may be used as treatment for water that is produced by pumping tests. Pre-approval is necessary by Wisconsin’s wastewater program if discharge is to a storm sewer or surface water body. In some cases, a POTW (publicly owned treatment work) accepts untreated pumping test water at a low cost. The POTW will probably require test results from the well pipe to approve the discharge. It may require testing of other parameters in addition to those required by LUST, ERP or Superfund program requirements, such as BOD5 or suspended solids. The local POTW should be contacted to determine necessary analytical requirements.

Designers should evaluate the means and costs of water disposal when determining which aquifer characterization method to use.

Hydraulic conductivity estimates

Designers use the following methods for estimating hydraulic conductivity:

- grain-size analysis
- bail-down and slug tests
- pumping tests

Grain-size analysis. A mathematical determination of hydraulic conductivity based on grain size is rarely appropriate for designing a groundwater extraction system. A grain-size test may be used in unconsolidated material to corroborate other tests. The reasons for poor performance of this test include the following:

- many methods exist, yet no single test has proved to be best under all conditions
- most methods are applicable to sand; the Hazen method is valid only for a grain size of 0.1< D10< 3.0 mm, and the Masch and Denny method is limited to samples of unconsolidated sand
- samples collected for grain-size analysis are from very small discrete locations; often only one to three samples are tested; therefore, only a few discrete parts of the site are used to estimate the overall site hydraulic conductivity and transmissivity
- some methods disregard soil density, porosity and grain roundness
- only groundwater flow through primary porosity in soil is evaluated in a grain-size test; if there is flow-through secondary porosity—such as fractures in till—the conventional tests are invalid

Bail-down (water-table wells and piezometers) or slug tests (piezometers) provide better hydraulic conductivity estimates than grain-size analyses. (For the purposes of this article, a bail-down test instantaneously extracts or withdraws a volume of water or a slug from the well, and a slug test instantaneously injects a solid slug into the well. Wisconsin administrative code defines a piezometer as a monitoring well with the entire screened section of the well below the water table.)

Slug tests are conducted in piezometers **and only in piezometers**. A slug test in a water-table well will force water into the unsaturated filter pack and possibly into the unsaturated native soils, increasing the length of submerged screen. Changing the submerged screen length during the test invalidates the test.

Bail-down or slug tests may not provide the most accurate results for the following reasons:

- only the part of the aquifer immediately adjacent to the filter pack and screen is evaluated
- when testing water-table wells, only the uppermost part of the aquifer is tested; more representative results are obtained from wells that reflect an overall average of the aquifer
- piezometers test only a very small part of the aquifer in the vertical dimension because piezometer screens are usually only five feet long and the sand pack is seven to eight feet long
- if flow exists in secondary porosity channels, the wells may not intersect channels or fractures and the test would only evaluate the primary permeability; if the well intersects a fracture, the interpretation could also be inaccurate because the assumptions in the conventional methods are violated
- inadequately developed wells will not yield meaningful results; borehole smearing during drilling will cause the well to reflect an artificially low permeability (In Wisconsin, wells not developed to Chapter NR 141 standards typically do not provide accurate hydraulic conductivity estimates with slug or bail-down tests, and these wells should be redeveloped.)
- high-permeability aquifers often yield artificially low estimates with slug/bail-down tests because the injection/extraction relative to the rate of the induced inflow/outflow from the aquifer are not instantaneous
- if the filter pack is less permeable than the native soil, the calculated hydraulic conductivity is artificially low because the test measures the hydraulic conductivity of the filter pack; a too-small screen slot size can limit groundwater flow into a well, lowering the hydraulic conductivity estimate in highly permeable aquifers

Pumping tests extract groundwater at a constant rate for a number of hours. A step-drawdown test varies the pumping rate over time. These tests are used to calculate the aquifer transmissivity and specific yield or storage coefficient.

In some cases, pumping tests will require an additional monitoring well or aquifer-test well. A pumping test can be performed in an aquifer-test well constructed for the pumping test, a groundwater extraction well, or an oversized (4-inch) monitoring well. An aquifer-test well should be evaluated for entrance velocity prior to well installation. A wire-wrapped screen may be necessary in highly permeable aquifers to reduce entrance velocity. In this case, incrustation due to a high entrance velocity is not an issue because of limited pumping duration, but flow restriction through too small a slot size could occur.

A well screen longer than normally used for a monitoring well may also be necessary to achieve the desired drawdown and flow rate during the pumping test. If the aquifer-test well is upgradient of the source and within the same geologic unit, it may produce clean water. Disposing of clean water from a pumping test is much easier than disposing of contaminated water, which may be a factor when planning the test's duration and pumping rate.

Some general considerations for pumping tests follow.

1) A method that accounts for partial penetration and/or unconfined conditions is appropriate in most aquifer-decontamination projects. The groundwater below a partially penetrating extraction well, however, is relatively stagnant and does not "flow" during the test; therefore, this portion of the aquifer is not "tested". Methods that assume a fully penetrating well could result in an artificially low transmissivity. Partial penetration effects are minimized at a distance (from the extraction well) that is twice the aquifer thickness. Therefore, methods based on fully penetrating wells (including the Jacob straight-line method) can be used on data from monitoring wells that are a significant distance from the extraction well. If the Jacob straight-line method is used, the calculated u value should be less than 0.05. W(µ)is known as the well function; µ = r2S / 4Tt (see "Jacob straight-line method" in definitions on page 11).

2) The classic pumping test for a water-table aquifer is a 72-hour test. Confined aquifers may need only a 24-hour test. At some small sites, a low-capacity test (less than 10 gpm) for a shorter time period (8 to 24 hours) may be sufficient. Pumping test length may be modified depending on analysis of initial test data. If data suggests that the drawdown in an unconfined aquifer has stabilized, the pumping test should continue long enough to ascertain that a delayed yield or slow drainage effect is not influencing the results.

3) Water-level measurements should be collected at all available measuring points. Even distant points that are outside the radius of influence provide data on background water-level fluctuations during the test. Hydrogeologists should collect water and product level measurements in wells with floating product. Wells with floating product, however, should not be used for pumping test evaluation unless there is a well shortage at the site. Because the dynamics of multi-phase fluid flow into and out of a well with floating product may introduce error, these monitoring wells may provide misleading information. If wells with floating product are used, the density of the product should be estimated to calculate the equivalent head in the well.

4) In all cases, recovery data for a pumping test is collected and evaluated, especially at the groundwater extraction well.

5) Casing storage can influence early drawdown data in large-diameter wells that are installed in relatively impermeable aquifers.

In some cases, a short step-drawdown test using small-diameter electric submersible pumps is a viable alternative to a full-scale pumping test. If a 4-inch monitoring well is used at the site, a higher capacity step-drawdown test can be conducted.

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Definitions of some common hydrogeological terms

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

Aquifer test Determines hydrologic properties of the aquifer. This involves withdrawing measured quantities of water from or adding to a well, and the measurement of resulting changes in head in the aquifer both during and after the period of discharge or additions.

Aquifuge A hydrogeologic unit that has no interconnected openings and hence cannot store or transmit water; an impermeable rock.

Aquitard A confining bed that retards but does not prevent water flow to or from an adjacent aquifer; a leaky confining bed; it does not readily yield water to wells or springs, but may serve as a storage unit for groundwater.

Confined aquifer Completely saturated aquifer whose upper and lower boundaries are impervious or at least of distinctly lower permeability than the aquifer; the pressure of the water is usually higher than that of the atmosphere, and water in wells stands above the top of the aquifer. Water in the confined aquifer is called confined or artesian water.

Darcy's law Rate of flow through a porous medium that is proportional to the head loss, inversely proportional to the flow path length, and proportional to a coefficient, k:

$Q = kiA$ or $Q/A = v = ki$

Where

Q = flow rate (m^3/day)

k = a constant (m/day) that should not be confused with velocity

i = the hydraulic gradient, the loss of head, h, over the distance (dimensionless)

A = the total cross-section perpendicular to the flow (m^2)

v = the flow velocity

Groundwater That part of the subsurface water that is in the saturated zone.

Head, static The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point; the static head is the sum of the elevation head and the pressure head.

Head, total The total head of a liquid at a given point is the sum of three components: elevation head, which is equal to the elevation of the point above a datum; pressure head, which is the height of a column of static water that can be supported by the static pressure at the point; and velocity head, which is the height to which the kinetic energy of the liquid is capable of lifting the liquid.

Hydraulic conductivity A proportionality constant relating hydraulic gradient to specific discharge. For an isotropic medium and homogeneous fluid, this constant equals 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 flow direction. When the hydraulic conductivity of the aquifer material is high, the cone of depression induced by pumping will be wide and flat. When the hydraulic conductivity is low, the cone of depression will be steep and narrow.

Hydraulic gradient The change in static head per unit of distance in a given direction; if not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Jacob straight-line method Data analysis method whereby a straight line is drawn through field data points (head) and time and extended backward to the zero drawdown axis where

$$h_o - h = (2.3Q/4\pi T) \log_{10} (2.25Tt/Sr^2)$$

$h_o - h$ = drawdown

Q = well discharge

T = transmissivity

t = time since pumping began

S = storativity

r = distance to the observation well

Leaky or semi-confined aquifer Completely saturated aquifer that is bounded above by a semi-pervious layer and below by a layer that is either impervious or semi-pervious. A semi-pervious layer has a low but measurable permeability; lowering of the piezometric head by pumping will generate a vertical flow of water from the semi-pervious layer into the pumped aquifer.

Piezometer Device to measure groundwater pressure head at a point in the subsurface.

Piezometric head Elevation of the water level in a piezometer with respect to a reference level, generally sea level (m); the piezometric head has the dimension of length.

Continued on next page

Definitions of some common hydrogeological terms

(continued from page 11)

Piezometric surface Imaginary surface through all the points to which the water rises in piezometers penetrating the aquifer.

Phreatic or free water table Height at which the pressure of groundwater equals that of the free atmosphere; in general, the level at which water stands in shallow boreholes and wells. An alternative definition is the uppermost location where the soil (or rock) is completely saturated with groundwater. In practice, the first definition is generally considered to be correct, but if remediation activities such as soil venting are used, the second definition may be more appropriate.

Semi-unconfined aquifer An aquifer intermediate between semi-confined and unconfined where the hydraulic conductivity of the fine-grained layer in a semi-confined aquifer is so great that the horizontal flow component in the covering layer cannot be ignored.

Specific yield Volume of water released or stored per unit surface area of the aquifer per unit change in the component of head normal to that surface; a dimensionless parameter that refers to the unconfined parts of an aquifer; in practice, it may be considered equal to the effective porosity or drainable pore space because the effects of aquifer material and fluid elasticity are negligible with unconfined aquifers.

Storage coefficient This term is also defined as volume of water released or stored per unit surface area of the aquifer per unit change in the component of head normal to that surface; however, storage coefficient refers ***only*** to the confined parts of an aquifer and depends on aquifer material and fluid elasticity.

Transmissivity or transmissibility The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient; it is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths. Also, the product of the average hydraulic conductivity (or permeability) and aquifer thickness; transmissivity is the rate of flow under a hydraulic gradient equal to unity through a cross-section of unit width over the whole aquifer thickness (m^2/day).

Unconfined aquifer Permeable bed only partly filled with water and overlying a relatively impervious layer; its upper boundary is formed by a free water table or phreatic level under atmospheric pressure.

Unsaturated flow Movement of water in a porous medium in which the pore spaces are not filled to capacity with water.

Unsaturated zone The zone between the land surface and the regional water table; generally, water in this zone is under less than atmospheric pressure, and some of the voids may contain air or other gases at atmospheric pressure.

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UTTU thanks George Mickelson, Wisconsin DNR, for contributing this list of articles.

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Publications

Publications that are available (view or download) from CLU-IN, http://clu-in.com/techpubs.htm (or call 800-424-9346 or 703-412-9810), include the following:

- *Clarification Regarding Use of SW-846 Methods* (memorandum)
- *Remediation Technology InfoBase: A Guide to Federal Programs, Information Resources, and Publications on Contaminated Site Cleanup Technologies* (EPA 542-B-98-006)

Aerobic Co-metabolic In Situ Bioremediation Technology Guidance Manual and Screening Software Users Guide, view or download at http://en.afit.af.mil/env/insitubio.htm.

Commercial Biosensors: Applications to Clinical, Bioprocesses, and Environmental Samples, 1998, is available from John Wiley Publishers, http://www.wiley.com, for $65.95.

Cumulative Risk Assessment Guidance—Phase 1 Planning and Scoping (memorandum and guidance document), view or download at http://www.epa.gov/swerosps/bf/gdc.htm#risk.

Environmental Change and Challenge: A Canadian Perspective, 1998, is available from Oxford University Press, http://www.oup.co.uk/, for $65.87.

Information Resources for Innovative Remediation and Site Characterization Technologies (EPA 542-C-98-003) is available from U.S. EPA, 800-490-9198 or 513-489-8190.

Principles of Soil Chemistry, 1998, is available for $79.75 from Marcel Dekker, http://wwwdekker.com/homepage/home_top.htm.

Technology Summary Report: In Situ Flushing (TI-98-01), view or download at http://www.gwrtac.org/html/tech_misc.html#FLSH08071998.

Watershed Restoration: Principles and Practices, 1997, is available from American Fisheries Society, http://www.fisheries.org/.

Websites and electronic documents

Biotech Dictionary: http://biotech.chem.indiana.edu/pages/dictionary.html

Bladder pumps: http://qedenv.com/qed.html

Concerted Action on Risk Assessment for Contaminated Sites in the European Union: http://www.caracas.at/

Dictionary resources: http://www.cs.nmsu.edu/~dtappan/dictionaries.html

Ecosystem Management Analysis Center: http://www.fs.fed.us/emac

Environmental Contaminants Encyclopedia: http://www.aqd.nps.gov/toxic/index.html

Environmental Defense Fund's Chemical Scorecard gives EPA toxic release inventory data: http://www.scorecard.org.

Environmental health and safety, education and training: http://www.ehsn.com

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UTTU obtained many of these sites and other information from the Groundwater Mailing List (http://www.groundwater.com), Bioremediation Discussion Group (http://biogroup.gzea.com, TechDirect (http://clu-in.com/techdrct.htm) and Environmental Science and Technology (http://acsinfo.acs.org/journals/esthag/). UTTU thanks the moderators from the on-line groups: Ken Bannister of Groundwater, Richard Schaffner of BioGroup and Jeff Heimerman from U.S. EPA's TechDirect.

The view from U.S. EPA: December 1998 UST deadline

The following is a summary of the speech that Anna Hopkins Virbick, director of OUST, U.S. EPA, made to the members of the Public Risk Managers Association (PRIMA) regarding the December 1998 deadline. PRIMA's members include local and state government people who are both regulators and regulatees.

In 1984, Congress responded to the increasing threat to groundwater from leaking USTs by adding Subtitle I to the Resource Conservation and Recovery Act. This section of the law required U.S. EPA to develop a comprehensive regulatory program for USTs. Congress directed U.S. EPA to publish regulations that would require owners and operators of new tanks and existing tanks already in the ground to

- prevent and detect releases
- clean up releases
- demonstrate financial responsibility for cleaning up releases and compensating third parties for resulting damages

U.S. EPA promulgated the technical regulations for USTs on September 23, 1988. Financial responsibility regulations were promulgated on October 26, 1988.

The technical requirements were created to help prevent UST releases. States report that UST releases are the most common source of groundwater contamination, and petroleum the most common contaminant. UST releases have caused some fires and explosions, while gasoline fumes have contaminated buildings. Over 360,000 UST releases have been documented thus far. Financial responsibility requirements were designed to ensure that money will be available for cleanups and third party compensations.

When developing the regulations, U.S. EPA provided numerous compliance options and phased in compliance for many regulations in order to give flexibility to UST owners and operators, especially smaller businesses. U.S. EPA also designed the UST program to be implemented by states. Ten years after those regulations were promulgated, states, with assistance from U.S. EPA, have made tremendous progress on

- overseeing the proper closure of more than one million substandard USTs
- ensuring the use of leak detection and leak prevention technologies on hundreds of thousands of active USTs
- overseeing and/or funding the cleanup of hundreds of thousands of UST releases

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Still, more than 900,000 active USTs exist nationwide, a significant number of which require upgrading, replacement, or closure by December 22, 1998. In addition, some of these USTs have not yet met requirements for release detection, a strategy that gives an early warning signal for a UST release. Ensuring that these tanks come into full compliance will prevent another generation of leaking USTs and fulfill U.S. EPA's mandate of protecting human health and the environment. In addition, cleanup work at hundreds of thousands of UST sites must continue.

Below are the three options for existing USTs (USTs installed before December 22,1988), one of which must be met by December 22, 1998:

- replace with new UST installation, or
- upgrade existing UST to meet standards for protection from spills, overfills, and corrosion, or
- properly close UST according to federal requirements

Estimates for minimum compliance costs for these options, for an average 3-tank facility, are

- $75,000 for installing new USTs
- $10,000 for upgrading existing USTs
- $10,000 for properly closing existing USTs

These estimates do not include cleanup costs that may occur during these activities.

Many nonmarketers, including public entities such as local governments and schools, originally owned and operated UST facilities for convenience. But USTs can create potentially big liabilities because of compliance and cleanup costs. The U.S. Postal Service found in many cases that it was cheaper and easier to buy fuel for its vehicles from retail gas stations than to own USTs.

In 1989, U.S. EPA worked with the National Association of Towns and Townships (NATaT) to identify solutions and options for small communities to comply with the UST regulations. NATaT describes these options in "Getting Out From Under: Underground Storage Tank Alternatives for Small Towns."

The state UST programs can also provide information regarding specific state requirements that may differ from the federal requirements. While state requirements may not be less stringent than the federal requirements (by law), they may be more stringent. Also, twenty-six states and the District of Columbia and Puerto Rico have received approval from U.S. EPA to run their own programs.

To obtain more information about the UST requirements, to order compliance assistance materials, and to find appropriate contacts at state and regional environmental offices, see OUST's website at **http://www.epa.gov/oust** or contact the hotline at 800-424-9346.

U.S. EPA recently released its strategy for enforcing the 1998 UST deadline, a strategy developed after consultation with the states. The strategy's main messages are

- U.S. EPA will hold firm to the December 22, 1998 deadline
- states and U.S. EPA intend to enforce the regulations
- states will continue to be the primary implementing agencies
- U.S. EPA will augment and assist state efforts
- U.S. EPA will be the primary implementing agency in Indian Country

UST owners and operators who have not complied with the 1998 deadline can be cited for violations. Fines can exceed $11,000 a day.

Underground Tank Technology Update

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University of Wisconsin–Madison

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