Chapter 2
Suggested Minimum Baseline Data for Each Well

2-1. Causes of Well Problems

a. Cause summary. HTRW well-system problems have a number of identified causes (Driscoll 1986; Borch, Smith, and Noble 1993; Smith 1995; Alford and Cullimore 1999) that often work together to produce conditions encountered on the well site. Table 2-1 summarizes problems with wells.

b. Symptom determination. In many cases, symptoms of well deterioration may not be apparent until well performance is severely impaired, unless the results of system water and quality and performance monitoring are compared over time to establish trends. Such problems can be prevented and mitigated by effective O&M, but to do so requires valid information on the environment, hydrology, and material performance of the well system produced by information collection in the process known as “maintenance monitoring.”

c. Purpose of maintenance monitoring. Maintenance monitoring is one aspect of well problem prevention, and includes maintenance and rehabilitation that is employed to provide early detection of deterioration of wells. The ideal situation is to detect deteriorating effects in time to prevent problems or allow the easiest possible treatment. Table 2-2 summarizes useful well information to collect for troubleshooting and predicting problems.

d. Minimum analysis goals. At a minimum, a preventive maintenance (PM) monitoring program should provide regular analyses to determine:

- Whether a deteriorating condition may be occurring.
- The reasons for changes in well and pump performance and water quality as soon as the changes can be detected.

e. PM monitoring information use. In order for O&M to make use of such information over time:

- A maintenance system must have organized and accessible records.
- Information collection should begin with the project design phase and continue throughout the working life of the extraction and injection system.
- Records must be regularly reviewed by qualified personnel.

f. Adjusting maintenance monitoring protocols. In general maintenance monitoring approaches should be tried and reviewed over a period of time and adjusted based on experience. They must be implemented as part of a systematic maintenance program involving:

- Institutional commitment.
- A goal of deterioration prevention.
- Systematic monitoring as part of site maintenance procedures.
- A method evaluation of information to determine what maintenance actions are necessary.

In any case, it has to be recognized that monitoring approaches and responses will be site specific, and likely will require adjustment during implementation.

Table 2-1. Definitions of Poor Well Performance and Causes

Problems	Causes
Sand/Silt Pumping: Pump and equipment wear and plugging.	Inadequate screen and filter-pack selection or installation, incomplete development, screen corrosion, collapse of filter pack due to washout resulting from excessive vertical velocity in the filter pack, presence of sand or silt in fractures intercepted by a well completed “open-hole,” incomplete casing bottom seat (casing-screen break) or casing-screen break due to settlement, ground movement, or poor installation. Pumping in excess of gravel pack and system capacity (oversized pump, pipe breakage lowering pumping head, etc.).
Silt/Clay Infiltration: Filter clogging, sample turbidity.	Inadequate well casing seals, infiltration through filter pack, or "mud seams" in rock, inadequate development, or casing-screen break due to settlement, ground movement, or poor installation. Formation material may be so fine that engineered solutions are inadequate.
Pumping Water Level Decline: Reduced yields, increased oxidation, well interference, impaired pump performance.	Area or regional water-level declines, pumping in excess of sustainable well capacity, well interference, or well plugging or encrustation. Sometimes a regional decline will be exaggerated at a well due to plugging.
Injection water level rise and reduced acceptance rate or increased injection system head.	Area or regional water-level rise; injection in excess of sustainable well capacity; well plugging or encrustation; encrustation, plugging, or corrosion and perforation of discharge lines; increased TDH in water delivery system.
Lower (or Insufficient) Yield: Unsatisfactory system performance.	Dewatering or caving in of a major water-bearing zone, pump wear or malfunction, encrustation, plugging, or corrosion and perforation of discharge lines, increased total dynamic head (TDH) in water delivery or treatment system.
Complete Loss of Production: Failure of system.	Most typically pump failure. Also loss of well production due to dewatering, plugging, or collapse.
Chemical Encrustation: Increased drawdown, reduced output or reduced injection acceptance rate.	Deposition of saturated dissolved solids, usually high Ca, Mg carbonate, and sulfate salts or iron oxides, or FeII sulfides. May occur at chemical feed points, e.g., feeding caustic soda to raise pH into a Ca-rich water.
Biofouling Plugging: Increased drawdown, reduced output or reduced injection acceptance rate, alteration of samples, clogging of filters and lines.	Microbial oxidation and precipitation of Fe, Mn, and S (sometimes other redox-changing metals that are low solubility when oxidized) with associated growth and slime production. Often associated with simultaneous chemical encrustation and corrosion. Associated problem: well "filter effect": samples and pumped water are not necessarily representative of the aquifer. Often works simultaneously with other problems such as silting.
Pump/Well Corrosion: Loss of performance, sanding, or turbidity.	Natural aggressive water quality, including H_2S, NaCl-type waters, biofouling and electrolysis due to stray currents. Aggravated by poor engineered material selection.
Well Structural Failure: Well loss and abandonment.	Tectonic ground shifting, ground subsidence, failure of unsupported casing in caves or unstable rock due to poor grout support, casing or screen corrosion and collapse, casing insufficient, local site operations.

Table 2-2. Parameters Useful in Well Maintenance Monitoring

Type Tests	Parameters Obtained
Hydraulic testing	Flow and drawdown for specific capacity (water level rise in injection wells).
	Total amount of pumping time and quantity pumped per year.
	Periodic step-tests for well and pump efficiency.
	Power and fuel consumption for pump efficiency.
Physicochemical parameters (for changes due to deterioration)	Total and ferric iron, and total manganese (and other metals as indicated).
	Important anions as identified, including sulfides, sulfates, carbonates, and bicarbonates.
	pH, conductivity, and redox potential (Eh) where possible (instrument readings may be replaced by checking ratios of Fe (total) to Fe^{2+} (soluble)).
	Turbidity or total suspended solids calculation of product water.
	Calculation of corrosion/encrustation potential using a consistent method.
Microbial	Total Fe/Mn-related bacteria (IRB), sulfur-reducing bacteria (SRB), slime-forming and other microbial types of maintenance concern as indicated.
Visual/physical	Pump and other equipment inspection for deterioration
	Borehole TV for casing and screen deterioration.

g. Incorporating PM data collection into the site data collection effort. Too often the significance and central importance of data are overlooked in the context of the scope of the whole project. What may seem to be minor clerical details to those responsible for a project's overall management can be important later in site operations. The quality and completeness of boring logs, well completion diagrams, and well testing, etc., are often left to contractors who do not appreciate the value of the data, or left to inexperienced, overworked, or unsupervised junior technical staff. Omissions in the data are often apparent only when it is too late to correct the deficiency.

(1) Data are easiest to obtain and more accurate if data collection is incorporated into the project plan at the onset. There is a tendency to omit maintenance planning, data gathering, and repair costs when bids are higher than budgeted, or to inadequately fund these tasks as costs are adjusted to available funds during project management. Budgets to fund remediation activities themselves can be unrealistic in this regard in not adequately considering the real costs of maintenance.

(2) Compiling data at a later stage of a project's operation is generally difficult and less successful. The following sections describe the types of testing and information recommended, and how the information should be collected, recorded, and managed, along with useful references and standards in practical use. A minimum of baseline data on each well is needed to assess and interpret the well's performance through time. Specifications should assure that there are specific requirements for data collection and analysis for O&M purposes.

2-2. Well Tests: Purpose and Description

a. General. Reliable, valid tests are critical to well assessment and management. Such assessment and management is enhanced by a history of valid well data over time, back to installation if possible (Chapter 3). Valid results depend on their reliable, valid, and reproducible test design, performance, reporting, and interpretation. In practice, performance and proper reporting of results lag behind performance standards. This pamphlet briefly reviews pumping test types and how they are used to assess pump, well, and pumped-formation (aquifer) parameters. It describes minimum valid baseline data to be reported, including

- Minimum data standards for tests.
- Minimum data for individual water level measurements (not just final levels), pumping rates, sand (particulate) or colloidal content, and information on conditions that would affect results.
- How to determine adequate testing intervals.

b. Data collection.

(1) Accurate discharge flow data are needed for any pumping test. All devices should be calibrated prior to installation, and at regular intervals to ensure proper operation. Flow measurement devices suitable for pumping tests include:

- Orifice weirs: Driscoll (1986) provides a detailed description of the necessary elements of the construction and use of an orifice weir.
- Mechanical flow meters which may also be used.
- Sonic-based flow meters available that are accurate and well adapted to this application.

(2) Equally important are time and water level measurements throughout the test. The times of measurements must be accurately reported and the water levels themselves reported accurately in decimal units (for analysis input). If there is the potential for water cascading in the well during the test, fit the well with a drawdown (stilling) tube to shield the water level probe from the cascading water and ensure accurate water level measurements. Finally, the data must be recorded on a sheet specifically structured to record and organize pumping test data (an example is supplied in Appendix D). Directly measuring system gauge pressure is essential in evaluating pump performance and useful in making field decisions on tests of relatively unknown wells or pumps.

c. Step-drawdown tests. Step-drawdown tests are probably the most valuable hydraulic testing tool available for assessing well performance in the context of maintenance and rehabilitation. When properly conducted and analyzed, they provide data on specific capacity and well and aquifer losses. Additionally, from the analysis, well efficiency and drawdown and specific capacity at a given discharge rate can be estimated.

(1) Conducting and analyzing step-drawdown tests are treated in detail in Kruseman and de Ridder (1994). For porous medium aquifers, the Hantush-Bierschenk method of analysis is employed, which is relatively straightforward. For fractured rock aquifers, Rorabaugh's method may be required, which is less straight forward. A computer application to solve Rorabaugh's method, such as FASTEP (Labadie and Helweg 1975), may be useful. Plate D-2 is an example step drawdown plot. Plates D-3 and D-4 provide an analysis of the step-drawdown test charted in Plate D-2 to determine well and aquifer loss. Plates are provided in Appendix D.

(2) The utility of data derived from the step-drawdown test is in the ability to:

- Determine characteristics about both the well and the aquifer simultaneously (aquifer and well loss).
- Extrapolate or interpolate the performance of the well at various discharge rates, using measured data points as a reference.
- Determine the operating characteristics of the well pump used.

(3) If performed immediately after a well is constructed, the step-drawdown test provides an estimate of the efficiency of the well and effectiveness of the well development phase of the well construction, and the baseline well and pump performance for comparison in the future. First checks of a well design's criteria or assumptions can also be made and adjusted as needed. It is highly recommended that all of these wells be pre-developed immediately after the well screen and filter pack are installed. This procedure gives a far greater chance of removing both drilling fluid solids and natural fines, and of replacing any of the filter pack that subsides due to consolidation, etc.

(4) Note that well loss does not increase linearly to the discharge rate; therefore, well efficiency and specific capacity are not constant and decline with increasing discharge rate. This relationship makes comparing well performance data through time and various discharge rates difficult without normalizing the data to the same discharge rate. The equation describing well and aquifer loss to interpolate or extrapolate pumping water levels should be used as needed. The equation can also be used to estimate specific capacity and efficiency at the intended discharge rate. Changes in well performance will then be apparent.

(5) For step-test data to be useful in calculating well, pump, and aquifer performance parameters:

- Data must be accurately gathered, with data collected at standard intervals of decreasing frequency as recommended (Helweg, Scott, and Noble (1983), and Driscoll, 1986).
- Each step must be of a sufficient length of time for either the water level decline to stabilize or the decline trend to be established on a semi-log plot of drawdown versus time (but does not have to be long).
- The effects of interference (such as other wells turning on and off) must be factored into the analysis.

(6) HTRW sites may impose restrictions on optimal step testing methodology. For example, a five-step test with pressure measurement is recommended to determine pump wear. However, pumping contaminated ground water requires collection of the fluid. Perfecting the gathering of pump wear data from a three-step test, and learning to extrapolate from short steps may be a necessary compromise in methodology.

d. Constant rate and slug tests. Constant rate pumping tests and slug tests (in which an instantaneous charge of water or a solid object is introduced into a well) are employed predominantly to determine aquifer characteristics, that is, transmissivity, hydraulic conductivity, and storage coefficient. Their utility in well maintenance and rehabilitation is less direct than with step-drawdown tests, but data derived from these tests can be used in preliminary calculations of expected well hydraulic parameters.

(1) Constant-rate pumping tests.

(a) With knowledge of aquifer characteristics, the theoretical drawdown in the aquifer at the well screen for a given discharge rate can be calculated and compared with the observed drawdown at the same rate, yielding the well efficiency at that rate. As a constant rate test approaches steady-state, the final specific capacity at the discharge rate can be calculated. Neither the constant-rate or the slug test can provide the means for predicting the well loss and the well efficiency that occurs over a range of discharge rates. A step-drawdown test is needed.

(b) The constant rate test is conducted similarly to the step-drawdown test. As with the step-drawdown test, accurate discharge, water level, and time measurements are essential. Again, Kruseman and de Ridder (1994) provide an in-depth discussion of conducting and analyzing these tests. Computer applications are available to aid in the analysis of constant rate tests. Boulding (1995) provides a useful conceptual review of pumping test software which can be updated by research into current products.

(2) Slug tests. A slug test is also used to determine aquifer characteristics, not well performance, and involves a different procedure and methods of analysis.

(a) Descriptions of procedures and methods of analysis are provided in Kruseman and de Ridder (1994), Bouwer and Rice (1976), Hvorslev (1951), and ASTM D 4044, D 4050, and D 4104. The computer applications available to aid in the analysis of constant rate tests, such as AQUITEST (Walton 1996), also provide analysis of slug tests. Because of the small volumes of water involved and the short (or long) time span over which the test occurs, pressure transducers and digital data logging are generally employed. Pressure tranducers are submerged in the well and register the pressure of the column of water overlying them. Water-level changes are detected as changes in pressure as the height of the overlying water column either increases or decreases. The data logger can be programmed to sample and record data from the transducer at required time intervals. This feature of digital data logging is most useful when conducting slug tests in high-permeability sediments where many water level measurements will be required over a span of seconds as the water level rapidly recovers.

(b) As with constant rate pumping test data, calculations of aquifer characteristics based on slug test data can be used for estimation of theoretical well mounding in injection wells.

2-3. Specific Capacity Data

a. Definitions. Specific capacity is a term used to express the productivity of a well, and is defined as Q/s, where Q is the discharge rate and s is the drawdown in the well (Driscoll 1986). The observed drawdown in the well is a function of aquifer and well loss; therefore, Q/s is a term incorporating both aquifer and well performance. Step-drawdown tests described in Section 2-2 provide a means of separating the aquifer and well loss components.

b. Use of Q/s calculations. Q/s calculations, using water-level change and well pumping data, are used to assess pumping well performance and results of development and redevelopment (Helweg, Scott, and Scalmanini 1983; Driscoll 1986; Borch, Smith, and Noble 1993). The data that need to be collected (Q and s in pumping wells) are simple to obtain and the calculations simple to make. Specific capacity and specific acceptance are relatively sensitive indicators of hydraulic performance change in wells. Making valid calculations in turn depends on reliable data collection. Appropriate actions in response to changing values depend on setting action levels that permit a response before performance is seriously impaired.

c. Minimum data needed and standards for data gathering, reporting, and assessment. To determine Q/s for a well, accurate static water-level, pumping water-level, and discharge rate data are needed. Since the water table or potentiometric surface varies seasonally and with outside stresses, a deeper pumping water level for a given discharge rate may not reflect a change in the well performance. Therefore, some means will be required to determine the variation in the static water level, e.g., an observation well outside the influence of the pumping well or static water levels obtained when the well is not pumped.

d. Effects on Q/s calculations. Static and pumping water levels can be affected by oscillations caused by the pump, cascading water, the water level probe becoming entangled in wiring and pump column, and operator error.

(1) Many problems can be avoided by installing a stilling (drawdown) tube in the well. Also, clearly establishing the "measuring point" (MP) of the well from which all measurement are taken and informing all personnel who will be collecting data of the MP will avoid many problems. The discharge rate can vary in response to system back-pressure and changes in pump performance, and therefore cannot be assumed to be constant. It should be measured along with water levels when determining Q/s. The flow meter used to measure the discharge rate is also subject to error as it wears or clogs.

(2) It is desirable that a baseline Q/s be determined at the intended discharge rate when a well is constructed (assuming the efficiency of the well is acceptable). Subsequent measurements of the drawdown in the well and discharge rate and recalculation of Q/s will provide an indication of the ongoing performance of the well (Borch , Smith, and Noble, 1993; Howsam, P., Misstears, B., and Jones, C. 1995). See Chapters 4 and 5.

2-4. Development Data

a. Purposes of development. In well construction, development has three purposes:

- Repair damage done to the aquifer during drilling.
- Set the filter pack.
- Increase the permeability of the aquifer in the vicinity of the well.

b. Redevelopment. Later, development activities may be a component of a maintenance program to further the original development effort, or applied as a component of a maintenance program to maintain or restore a well's performance. In this use, the processes are termed “redevelopment.”

c. Development process description and importance. Detailed descriptions of development and redevelopment processes can be found in Australian Drilling Industry Training Committee Limited (ADITC) (1997), Driscoll (1986), NGWA (1998), and ASTM D 5521 (in the context of monitoring wells).

(1) Drilling method influence. The drilling method will, to some degree, modify or damage the aquifer material in the process of drilling the hole. One must know what damage or modifications are likely to have occurred in the aquifer material to judge the applicability or effectiveness of the development effort. This information is usually recorded on the drilling field log maintained by qualified oversight personnel. Each lithologic material will be uniquely vulnerable to the drilling process and may require specific development methods. Also, future performance problems may be related to aquifer lithology. Different well construction methods will require different methods of development and the construction of the well will determine what methods are applied in future activities. Additionally, the type of drilling method used tends to influence the method of development (if cable tool: surge blocks and bailers, if rotary: air compressors and pumps).

(2) Development methods. Well development includes as components many tools and methods and the development data should include descriptions of the tools and methods utilized. For example:

(a) If air lifting was applied, what was the size and capacity of the air compressor, at what depth was the airline set?

(b) If surging was applied, what was the configuration of the surge block assembly, does the diameter of the assembly match the casing and screen, through what intervals was it applied, and what was the length and speed of the stroke?

(c) If jetting was applied, what was the configuration of the jetting tool, through what intervals was is applied, etc. (nozzle velocity and distance from screen)?

(d) Other pertinent information, e.g., how much time was spent on each interval in cleaning.

(e) What predevelopment planning and decisions were made that would make development more or less likely to be successful?

d. Development data gathering. Valid and complete development information is necessary to assess results and to provide benchmarks for future development efforts. This information is recorded in a well development log and collected with drilling and well construction log information (see example forms in Appendix D). Minimum development information necessary includes:

(1) Drilling method description -- it affects development methods chosen and how field data are reported.

(2) Description of development procedures used -- air lifting, jetting, surge blocking, etc., including descriptions of equipment and capacities (e.g., air compressor cubic feet per minute (cfm) capacity).

(3) Time for each segment.

(4) Description of material drawn into well -- amount and type to determine its origin (need to know if it is aquifer or well pack), standards of development and how measured.

e. Integration of development data with other data. Development information is merged with step-drawdown data, well construction data, and lithologic data to provide insight into how the aquifer material has been modified or is behaving through time in the vicinity of the well. This insight is crucial for assessing changes in well performance and the appropriateness and effectiveness of maintenance and rehabilitation efforts.

f. Development data gathered and significance.

(1) Development time. The effectiveness of even an appropriate development method is related to the amount of time it is applied, and it must be determined if the time of application was sufficient for the method to be effective. Development data should include the amount of time devoted to each of the tools and methods mentioned above. The construction log may provide the amount of time devoted to development, or the work crews' time sheets or daily log may also provide the time devoted.

(2) Development results. The data should include some form of documentation of the progress of the development. Some drillers estimate changes in the discharge from the well during air lifting or surging to indicate the progression of development. The driller may record a qualitative description of the sediment and material removed from the well. A semi-quantitative record of the sediment concentration

may be had from allowing samples to settle in a bucket, and a quantitative record may be available if water samples were collected using an Imhoff cone or Rossum sampler. These and other methods are discussed in Driscoll (1986).

(3) Well acceptance tests. Finally, data from well acceptance tests, usually a step-drawdown test (Section 2-2), is helpful to document the effectiveness of the development. (As described in the discussion on step-drawdown testing, the resulting efficiency of the well can be estimated from the analysis of the test.)

2-5. Well Construction Diagram

"As constructed" well construction records are used in well maintenance to provide a basis for comparison of past and present conditions, and for use in other calculations. At a minimum, diagrams shall contain an accurate geographic location and precise designation used by the project, accurate depth, diameter (including different components), casing and screen material type, screen slot size and screen length, filter pack type, particle size and dimension, grout type and dimensions, and well equipment descriptions and dates drilled and developed. ER 1110-345-700 provides general guidance for plan components. EM 1110-1-4000 provides general guidance on well construction documentation. Plate 2-3 is an example well construction diagram.

2-6. Construction Boring Log

Boring logs include precise geographic location and boring identification (with cross reference to subsequent well designations), accurate formation descriptions (including sediment and rock descriptions provided according to uniform accepted standards with accurate depths), and particle size descriptions of water-producing/accepting zones.

a. Lithologic log. The lithologic log is a record of the character, depths, and thickness of geologic materials encountered by the drill as the borehole is advanced, with emphasis given to hydraulic properties of the materials. Lithologic logs should be recorded and maintained by qualified oversight personnel, using standard engineering or geologic terminology. EM 1110-1-4000 provides guidance on sample logging, the data to be recorded, and examples of forms used to record the data.

(1) The lithologic/boring log should contain as a minimum.

(a) The depth at which geologic changes occur and at which samples are collected and described.

(b) A description of cutting samples collected at every change of geologic materials and at 1- to 1½ -m (3.28- to 5-ft) intervals, and 100 percent logging for the screened interval in either the pilot or the final boring.

(c) Changes in drilling action, that is, penetration rate, fluid loss, drilling noise, etc.

(2) Descriptions of unconsolidated sediments should note dominant grain size, sorting, and estimates of relative percentages of sizes according to the Unified Soil Classification System (USCS) procedures and those described in ASTM 421 and 422. Grain shape and rounding are useful for estimating hydraulic properties. Color related to degree of weathering and oxidation-reduction is useful in determining degree of saturation. Descriptions of consolidated bedrock should note degree of cementation, induration, and fracturing. The depth at which saturated conditions occur should be noted. Changes in drilling fluid properties (gains or losses of fluids, changing specific gravity, etc.) should be noted, as they provide information on water-bearing zones.

b. Borehole camera survey. High-resolution borehole camera (still or video) surveys provide a means of recording lithology and fracture features in open boreholes, in addition to construction features. The camera provides depth-specific images for interpretation of lithologic features; for example, noticeable changes in formation color and texture, water cascading into the hole through fractures, and fracture orientations.

2-7 Pump, Flow Meter, Pressure, Electrical, and other Monitoring

a. Equipment and material choice importance in data gathering.

(1) Purpose. Meeting data-gathering goals requires apparatus that will provide the most accurate possible measurements. The equipment should be reliable and not distort measurements. To achieve these goals, the equipment should be well matched to the data-gathering needs and well operational environment.

(2) Material choices. The choice of materials to be used in devices for pumping and injection well performance is important to well system life and quality of service. For example, in most situations, where metals are specified, they should be stainless steel or other materials resistant to corrosion in the water being extracted. Materials should be specified based on analysis and experience under the environmental conditions to be found in the system. This requires analysis of the geochemistry of the fluid (Section 2-8) and comparison to the reactivity of materials proposed for use. This analysis should consider biological fouling and corrosion predictions (Section 2-9) because biofouling routinely introduces clogging and corrosive conditions where they might not occur in sterile fluids. Discussions of the material choice decision-making process are provided in numerous references (e.g., EM 1110-2-1914, EM 1110-1-4000, EM 1110-1-4008, and Powers, 1992; Borch, Smith, and Noble 1993; Smith 1995; and McLaughlan 1996 in the open literature specific to well maintenance).

(3) System component capacity. Pumps should be sized to closely match the well capacity and match the flow requirements and pressure head conditions in the system being supplied.

(a) Poor sizing affects performance adversely. Pumping well capacity can be established by step testing (Section 2-2). Flow and head conditions may be calculated, allowing for any likely fluctuations. Should as-built conditions differ from design conditions, pump selection should be reviewed to ensure that it matches the as-built hydraulics.

(b) EM 1110-1-4008 provides guidance in pump discharge head calculations. Pump sizing then can commence using standard ground water industry well pump sizing procedures. TI 814-1 provides sizing calculation procedures for submersible and vertical turbine pumps typical of remediation extraction wells. Powers (1992) provides design sizing methods for vacuum and ejector pump systems often employed.

(c) Once hydraulic head and flow conditions are used to design an ideal pump, comparisons can be made to pump capacity charts or pump curves generated by manufacturers and provided in the Contract Submittals (TM 5 813-9). See also discussion in Chapter 9 concerning material choices.

(d) An important feature is the location of the low water-level (lwl) shut-off, as specified by CEGS 11212. Manual override of the pump controls should not bypass the lwl shut-off.

b. Monitoring measurement systems. To obtain necessary baseline data, reliable methods of monitoring system parameters are needed.

(1) Water-level measurement recommendations include:

- Water-level data may be collected manually or the process automated.
- For relatively small numbers of wells and conditions where personnel are not at health risk when water columns are exposed, electric water-level probe and manual data entry may be used.
- For larger numbers of wells where personnel time would be inordinately devoted to water-level measurements, instrumented airline or automated water level recording via transducers is recommended.

For conditions where exposure to vapors off-gassing from well fluids poses an inhalation hazard, instrumented airline or automated water-level recording via transducers is recommended. Several approaches to water-level measurement are possible, each with its advantages and disadvantages. Table 2-3 summarizes these features.

(2) For flow measurements, each pumping well and receiving well or discharge should be metered. Total system pumping production should match total discharge. Imbalances may indicate leaks or metering inaccuracies.

(a) Flow meters should be sized to the expected flow. Instantaneous and totalized flow readings in commonly used volume-rate units (cubic meters/hour, gal/min, etc.) are necessary.

(b) Flow measurement method selections should take into consideration the quality of the fluid to be measured. High-solids, biofouling, or scaling water streams may foul turbine flow meters (TM 5-813-5, TI 814-3). Acoustic devices may have better service lives under some circumstances. Systems standard to industrial waste water treatment applications should suffice.

(c) At a minimum, measurements should be taken manually daily to weekly, depending upon fluctuation.

(d) Wherever possible, flow meters should have automatic readouts, either to a central SCADA system or readout device. Systems standard to industrial water supply should suffice. Calibrate the equipment at the frequency recommended by the manufacturer.

(3) For pressure measurement, either manually read or digital read-out meters may be used. With both, plugging of sensor orifices is to be expected. To detect pressure changes in the conveyance system, pressure should be measured as near as possible to the wellhead (immediately downstream of the pump discharge check valve). Measurements should be taken daily to weekly. Automation facilitates data collection.

(4) For electrical (power), measure changes in pump motor amperage (A) draw, circuit voltage (V), and resistance ohms (Ω) to detect problems in the electrical system. Portable equipment should be available for testing purposes.

(a) Voltage should be within +10 percent of the motor nameplate voltage when the motor is under load (running). Larger voltage variations may cause winding damage. These variations should be corrected in the power supply or the motor replaced to match the supplied voltage characteristics if the voltage remains constantly high or low.

Table 2-3. Features of Water-Level Measurement Methods

Type of water-level measurement	Advantages	Disadvantages
Electric sounder	Commonly available, reliable when maintained, accurate under most water-only conditions (+0.02 in.), not highly subject to downhole fouling. One sounder can be used on multiple wells.	Requires wellhead access and unobstructed water surface access, probe will foul in floating material on water surface, mechanical aging of conductor wire must be considered, cross-contamination is possible, requires personnel to take levels and manually enter data.
Airline (gauge measurement) or instrument measurement)	Inexpensive, no need for direct access to water level surface, each well has a dedicated airline.	Relatively inaccurate (+1 in. or more), subject to fouling, requires personnel for taking levels and manual entry of data.
Airline (instrument measurement)	Inexpensive, no need for direct access to water level surface, each well has a dedicated airline. With instrument, improves accuracy to electric water-level sounder range. Data recording possible.	Subject to fouling, requires personnel for taking levels.
Water level transducers	Relatively accurate when properly selected and maintained, permits automatic data querying in SCADA* system, dedicated to well, no personnel exposure to water, no direct water access needed.	Relatively expensive per unit, requires regular maintenance to deter fouling. If maintenance not performed, automatic systems may record inaccurate (useless) data.
* Supervisory, control, and data acquisition. Note that all these water level monitoring methods provide data that can be manually entered into SCADA databases. Note that all conventional water level measurement systems are fouled by non-aqueous-phase liquids and will yield inaccurate results.		

(b) Increases in amperage on start or run cycles over listed service factor amps indicate

- Loose terminals in the control box or possible cable defect.
- Too high or low service voltage.
- Motor windings are shorted.
- Mechanical resistance such as sand in bearings.

(c) A drop in typical “run” amperage indicates a loss of mechanical resistance against motor operation. This datum, in combination with reduced flow and/or pressure data, can be used to confirm that a problem has developed in pump output, such as if a hole has developed in the pump discharge pipe.

(d) Deviations in circuit ohms indicate wiring problems. Low values on one or more line legs indicates a potential motor short. Greater-than-normal values indicate poor cable connections or joints, or windings or cables may be open. If some values are higher than normal and others lower than normal, drop leads may be mixed.

(e) Megaohm detections outside the circuit indicate ground faults. For a motor installed in a well, if resistance between any wire lead and true ground is $<0.5\ M\Omega$, motor damage is likely to have occurred.

(f) Voltage imbalance in three-phase (3-ϕ) systems causes excessive motor aging and poor performance, and should also be checked routinely.

(g) Total kilowatt-hour (kWh) use can be used to calculate changes in motor and system efficiency.

(h) Electrical monitoring should be automatic if at all possible or, if manual, checked weekly. CEGS 13405 provides guidance in specifying apparatus for monitoring pump motor operation as well as the flow, temperature, pressure, and chemical-physical properties of the discharge. Particular attention should be paid to regularly monitoring wellhead voltage, amperage, Ω, and ϕ balance conditions of individual wells. Grounding should also be checked on a routine O&M schedule.

(5) For water sampling, strategically placed water sampling ports permit analysis of maintenance-related water quality parameters. A monthly to quarterly schedule is recommended (Section 5-1 to 5-3). Noncorrodible taps placed to permit sampling fluid at well discharge and other strategic points are necessary to detect indicators of chemical and biological clogging and corroding conditions. Where corrosion and biofouling are sampled directly using coupons (Smith 1992; McLaughlan 1996; Little, Wagner and Mansfield 1997), provision must be made for attachment of the necessary sampling devices and discharge of flow-through fluids. (Note: After any manual measurement or sampling, the location of the automatic lwl shut-off should be checked to verify that it was not adversely affected.)

(6) Measuring systems should be automated as much as possible. Measuring system maintenance must be integral with the well maintenance plan (Chapter 5).

2-8. Ground Water Geochemistry: Hazardous and Nonhazardous

a. Physicochemical data purpose. Physicochemical parameters are necessary to specify well materials, predict clogging and corrosive conditions, and plot environmental change. These parameters should be collected in the planning phase and during operation.

b. Physicochemical data analyses to be conducted.

(1) The basic, nonhazardous water chemistry data should begin with a standard set of constituents known as the “routine analysis for water quality” (Domenico and Schwartz 1990). This set of constituents is generally used for assessing the suitability of a water for human consumption and agricultural and industrial uses. The routine analysis includes the majority of the mass dissolved in the sample and that which remains unidentified is negligible. The routine analysis will also include other items, for example, pH, Eh (ORP or redox potential), and total dissolved solids (TDS). This analysis should enable one to identify the major ion species present, and the potential for deposition of solids.

(2) The routine analysis contains most of the major and minor ionic constituents, as well as a few of the minor constituents, if needed.

(3) Computer applications are available for organizing and plotting ionic constituent data that would facilitate tracking spatial or temporal variations in water quality (for example, HydroChem available from RockWare). Analyzing the chemistry data can be facilitated by utilizing programs such as WATEQ (Truesdell and Jones 1974), BALANCE (Parkhurst et al., 1982), and MINTEQ (U.S. EPA).

(4) Table 2-4 summarizes the purposes of specific physicochemical analyses recommended for use in identifying the mechanisms at work in ground water within the influence of the sampled wells. Analysis of geochemical mechanisms at work is crucial information in "triage" (Chapter 5) in which a determination is made of the appropriate levels of maintenance monitoring should be made. As specific redox-sensitive pairs important to a system are identified, these pairs can be monitored for change over time.

Table 2-4. Summary of Physicochemical Methods Relevant to Well Maintenance

Constituent Analysis	Purpose of Analysis
Fe (total, Fe^{2+}/Fe^{3+}, Fe minerals and complexes)	Indications of clogging potential, presence of biofouling, Eh shifts. Fe transformations are the most common among redox-sensitive metals in the environment.
Mn (total, Mn^{4+}/Mn^{2+}, minerals and complexes)	Indications of clogging potential, presence of biofouling, Eh shifts. Less common but locally important in some wellfields.
S (total, $S^{2-}/S^{0}/SO_4^{2-}$, S minerals and complexes)	Indications of corrosion and clogging potential, presence of biofouling, Eh shifts.
Eh (redox potential)	Direct indication of probable metallic ion states, microbial activity. Usually bulk Eh, which is a composite of microenvironments.
PH	Indication of acidity/basicity and likelihood of corrosion and/or mineral encrustation. Combined with Eh to determine likely metallic mineral states present.
Conductivity	Indication of TDS content and a component of corrosivity assessment.
Major ions	Carbonate minerals, F, Ca, Mg, Na, Cl determine the types of encrusting minerals that may be present and are used in saturation indices. One surrogate for many cations is total hardness.
Turbidity	Indication of suspended particles content, suitable for assessment of relative changes indicating changes in particle pumping or biofouling.
Sand/silt content (v/v, w/v)	Indication of success of development/redevelopment, potential for abrasion and clogging.
Note: Generally, the Fe^{2+}/Fe^{3+} ratio (easily measured using conventional field analysis instruments) is the most useful. In some settings, Mn oxidation (resulting in more difficult-to-remove minerals) and the sulfur system may be dominant.	

c. Hazardous physical/chemical parameters. Personnel safety (Chapter 7) dictates that physical (primarily radiological) and chemical conditions that will affect how maintenance can be performed should be known. For the most part, data collected for the purpose of regulatory monitoring (and its toxicological interpretation) should cover hazards of exposure to pumped fluids. Additional factors may include:

- Radon emission (hazard of exposure during long-term monitoring).
- Carbon dioxide, volatile organic gases, and hydrogen sulfide (hazard during confined space entry or long-term exposure).

d. Compatibility with well cleaning chemicals.

(1) Chemicals that may be used in maintenance treatment of wells (Chapter 6) may react unfavorably with pumped fluids to produce

- A hazardous personnel condition.
- Unexpected system damage.

(2) Potential reactions should determined prior to chemical application. Table 2-5 provides representative incompatibility relationships with compounds used in well treatment.

Table 2-5. Well Treatment Chemical Incompatibility

Chemical	Chemical Incompatibility
Acetic acid	Chromic acid, ethylene glycol, nitric acid, hydroxyl compounds, perchloric acid, peroxides, permanganates, and other strong oxidizers.
Acids (in general)	Sulfides, cyanide compounds, chlorates and perchlorates, ammonium nitrate, azides, alkali and alkaline earth metals, organic peroxides.
Carbon dioxide	Dusts of aluminum, manganese, titanium, chromium, and maganese suspended in carbon dioxide streams.
Chlorine	Anhydrous ammonia, ammonia, acetylene, butadiene, hydrocarbons, hydrogen, sodium carbide, turpentine, benzene, finely divided metals, activated carbon, any strong reducing compounds.
Chlorine dioxide	Organic materials, ammonia, methane, phosphine, hydrogen sulfide.
Halogens in general: (Strong oxidants)	Fuels, any flammable liquid, or other organic compounds.
Hydrofluoric acid	Aqueous or anhydrous ammonia, intensely corrosive to organics.
Hydrogen peroxide (Strong oxidant)	Copper, chromium, iron, most metals or their salts, alcohols, aniline, acetone, organic materials in general.
Hypochlorites	Acids (specifically HCl), activated carbon, other concentrated organic compounds, anhydrous ammonia.
Nitric acid (conc.)	Acetic acid, acetone, aniline, chromic acid, hydrocyanic acid, hydrogen sulfide, flammable liquids, flammable gases
Organic acids	Aluminum, arsenic compounds, strong reducing compounds.
Oxalic acid	Silver, mercury (forms low-solubility minerals in presence of calcium).
Potassium permanganate (Strong oxidant)	(Strong oxidant) glycerin, ethylene glycol, benzaldehyde, sulfuric acid, fuels, other organic compounds, flammable and explosive compounds.

(2) Persons designing any treatment involving fluids that contain strongly reactive, oxidative, reductive, explosive, or volatile compounds should specifically review chemical reactivity databases for conflicts. EM 385-1-1 provides guidance in health and safety physical/chemical reporting needs for health and safety.

2-9. Biological Assay

a. Purpose. Biofouling is historically a major or dominant component of corrosion and clogging impacts on ground water remediation systems (Leach et al. 1991; Smith 1995; Alford and Cullimore 1999). Section 4-6 reviews potential effects of system biological activity.

(1) From a maintenance standpoint, it is well recognized that early detection is crucial to the management of biofouling problems. However, it has always been difficult to correlate the results of testing for biofouling components and the degree of deterioration of components of wells. For example, samples that do not contain biofilm particulate matter and microorganisms do not necessarily indicate an absence of this material. Cultivating media may not support microorganisms that contribute to fouling, and sampling may not collect samples representative of the formation's and well system's microbial ecology.

(2) Smith (1992), Cullimore (1993), Smith (1996), and Alford and Cullimore (1999) discuss and provide guidance on biofouling assay methods and their utility in maintenance monitoring to provide useful information. With such information, the following questions can be readily answered:

- Is biofouling present?
- What types of biofouling organisms are present?
- Is the well more or less biofouled than before? The answer to this last question requires monitoring over time.

b. Mission of biological tests. Biological assay plans have differing strategies depending on the purpose of the study. Biological assays for maintenance monitoring have goals different from those for general aquifer ecology or bioremediation planning. Maintenance monitoring methods chosen should be task-oriented to detect those biological indicators or conditions that lead to reduced well system performance. For this reason, methods that provide rapid, general insight into biofouling and biocorrosive conditions are preferred over methods that characterize genetic makeup or metabolic capabilities.

c. Types of biological analyses employed in PM monitoring.

(1) Examination by light microscopy. This has traditionally been the method of choice for confirming and identifying "iron bacteria" (APHA, AWWA, and WEF, 1998, Section 9240). However, in many instances, biofouling as a cause of well problems may be difficult to diagnose via microscopy alone, even with very good tools and skills (Smith, 1996).

(2) Cultural enrichment.

(a) Culturing can provide a means to detect nonfilamentous, metabolically active biofouling microflora, and also to profile the ecological physiology niches occupied by microorganisms. Currently, the most promising cultural approach, from a practical application standpoint in the United.States., for routine maintenance monitoring purposes available in North America is the Biological Activity Reaction Test (BART) method (Cullimore 1993). This method was found by Smith (1992) in field trials to provide useful qualitative information in well biofouling events and is increasingly accepted as a standard biofouling monitoring method (Smith 1996).

(b) The BART method tubes come with a variety of media mixtures. The IRB-BART^{TM}0 , for example, is designed to recover anaerobic (sulfur- and nitrate-reducing) and microaerophilic heterotrophic Fe- and Mn-precipitating microorganisms (iron-related bacteria, IRB). Cullimore (1993), Smith (1992, 1996), and Alford and Cullimore (1999) provide guidance in BART method use. Smith (1996) is a proposed standard method, incorporating BART-type methods to replace the current (Section 9240 and ASTM D 932) standard methods that rely on microscopy alone. MAG tests (MAG Ltda., La Plata, Argentina) are a commercial alternative to some versions of BART (Gariboglio and Smith 1993; Smith 1996). In addition, bench-formulated liquid media may be used if preferred and facilities are available. Kissane and Leach (1993) (Appendix C) and Smith (1992) provide guidance in the context of well biofouling analysis. The commercial products eliminate the need to determine specific nutritional requirements and the facilities typically needed for environmental microbiology, and thus are more likely to be practical in maintenance monitoring use.

(3) Sampling issues.

(a) Cullimore (1993) describes a time-series pumped-sampling program that attempts to overcome the uncertainties of collecting particulates (biofilm components) by grab sampling. Cullimore's procedures involve taking advantage of the phenomenon that biofilm detachment occurs preferentially on start-up after a period of rest, in which the pump is allowed to shut down for a period of time from 2 hr to several days. This approach, which includes taking replicates of samples at each sample event, helps to overcome the statistical limitations of pumped grab sampling for cultural analysis.

(b) Grab samples remain unreliable for microscopic analysis (Smith 1992; Tuhela, Smith, Tuovinen 1993). For this purpose, some method is needed to provide enough sample to view or otherwise analyze mineralogically or chemically. Methods for collection of biofilm on immersed surfaces can provide essentially intact biofilms for analysis. These methods are also adaptable for collection of samples of inorganic encrustations and evaluating MIC effects (McLaughlan 1996; Little, Wagner, and Mansfield 1997). The flow cell system in Smith (1992) has been successful in practical use for such biofilm collecting. Sample collection using this method will be described in the Standard Methods 20th-Edition Supplement, Section 9240. Coupon sampling apparatus developed for MIC evaluation may also be used.

d. Minimum biological testing elements. At a minimum, a maintenance monitoring program for HTRW pumping and injection wells should include the use of tests kits (BART) and other self-monitoring systems (biofilm collection and visual inspection of components) on site, and visual inspection of equipment, at the least in a troubleshooting or baseline-monitoring role. Sample collection should follow the procedures of Cullimore (1993) for BART grab sample collection. Biofilm collection (either as a specific task or part of equipment inspection) can follow the protocol outlined in Smith (1996). BART testing and biofilm collecting can be conducted in a baseline troubleshooting role and then annually or at observed changes. Baseline-scheduled BART and other biofouling analyses are a useful part of “triage” (Chapter 5) for establishing maintenance protocols for new systems and documenting changes during operation when samples are collected regularly. Some sites may exhibit little or no change in biofouling analysis results once well systems are established and other sites may provide chronically aggressive results, so that BART analyses can be discontinued once the condition is documented. In these sites, biofouling analysis can be minimized.

2-10. Field Data Reporting and File Documentation

a. Purpose. The primary purpose for collecting, analyzing, and tracking trends in collected data is that there are many reasons why a well may experience diminished performance, and collected data are crucial for identifying causes. Also, once a pattern of well performance decline is established, collected data will enable the operators to plan maintenance and rehabilitation activities before a well is beyond recall.

b. Well data file features. Each well requires a comprehensive file of all data pertaining to its ongoing maintenance and performance history as well as the initial data pertaining to its construction, well performance, pump performance, water chemistry, and biological environment described above. Establishing this record system for each well should be done at the onset of the project. Since such data will periodically be manipulated and analyzed, a format for the records should be established that is compatible with the methods used for analysis. Consistency will save time and frustration, and improve accuracy.

c. File records purpose and format issues. Correct and relevant field data recording is essential for data to be of any value. How this is done can be project specific. HTRW projects, which are under regulatory supervision, by nature have in place systems to acquire, store, manage and report data sets. The data management system in place for the project in question can be adapted to provide the same activities for maintenance planning. Format issues include:

- Successful maintenance monitoring programs have been run using entirely physical paper files in the water supply field.
- Spreadsheet organization of data provides a tabular display of various data, permits plugging data into formulas to perform routine calculations such as those for specific capacity and motor efficiency, and permits rapid charting of data trends.
- Database systems permit cross-comparison of parameters to ascertain cause-effect relationships (e.g., changes in hydrocarbon concentration vs. head loss in pumping systems).

Storage and availability issues include:

- Copies of the spreadsheets should be kept on-site at the well field in individual log books for each well.
- Essential well data (depth, diameter, pump type, and identification) should be marked at the well.
- Accessible inventories of physical file components such as video tapes should be maintained so that people reviewing files may know what data are available. Chapter 8 provides checklists, and other chapter topics indicate data needs. These should be reviewed.

d. Types of records needed. Essential information includes:

(1) Physical locations and as-built descriptions of the wells and their equipment. The physical geographic location of each well should include reference to fixed landmarks as well as precise geographical coordinates such as provided by a geographical positioning system (GPS) for use in plotting using geographical information systems (GIS).

(2) As-built diagram of the well's construction, with any modifications over time.

(3) Lithologic log of the well as constructed, well drilling and construction logs, and any other logging data (caliper, gamma-gamma, etc.). Logs must be completely labeled with dates, depths, and borehole site identification. Copies of interpretation reports should be included in the file.

(4) Records of pumping tests and geophysical structure, borehole flow meter, etc., tests of the completed well over time.

(5) Pump performance data from pumping tests as applicable by date, including analysis and recommendations of pump performance reports.

(6) Pumping and static water levels by date and time of day.

(7) Dates of replacement of components, manufacturer and type of component, if known, and length of service, if known. Itemized invoices with costs should be included. Photos or video tapes should be made of deteriorated components for future reference, including descriptions. Copies of product owner operation and service literature should be included along with documentation of any contractor service personnel.

(8) Electrical, power and pump mechanical information.

(9) Water quality data from wellhead samples, plus biofilm collector results, listed by date. Labs and costs should be tracked, and should include reports analyzing water quality data.

(10) Electrical, power and pump mechanical (submittal literature, shop drawings, and nameplate) information.

(11) Details of well rehabilitation activities, including dates, diagnosis, if any, treatment methods, results, time involved, and costs.

(12) Color borehole TV survey videotapes. These should be taken at any zero point such as at well construction and at intrusive service intervals such as well rehabilitation to record visual changes in well conditions. Tapes may be consolidated as summary tapes of important well features over the years. Tapes should be labeled by well identification and date and stored properly in an accessible location.